Sahelian land-cover degradation and its effects on the silting-up of the middle Niger River

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THESE

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Résumé

Le principal objectif de ce travail est de comprendre l'impact du changement de couverture des sols sur la production et le transport de sédiments dans le bassin du fleuve Niger moyen. Ceci a nécessité des approches comprenant l'étude de données hydrologiques (1929 – 2008), de couvertures des sols (1965 – 2000) et des données sédimentaires mesurées (2005 – 2008). L'étude est centrée sur deux sous-bassins sahéliens (le Gorouol et la Sirba) comparés avec un sous-bassin soudanien (la Mékrou). L'augmentation des surfaces de sol nu, mesurée par télédétection, accroît le transfert de sédiments au fleuve par ses affluents jaugés comme par ceux, éphémères et non-jaugés, connus sous le nom de «koris», dont le nombre et la taille s'est beaucoup accru depuis les années 70. Les caractéristiques des sédiments, surtout celles des matières en suspension (MES) ont été mesurées à dix stations sur le fleuve et certains de ses affluents afin de quantifier le flux de sédiment et d'identifier les sources principales de sédiment. L'analyse hydrologique démontre l'impact de la diminution des précipitations sur les débits, la récente période sèche ayant modifié le régime du fleuve à Niamey avec un impact sur la forme du chenal. L'analyse du flux sédimentaire le long le fleuve indique qu'il y a d'autres sources importantes de sédiments outre les affluents principaux. Une simulation de la capacité de transport fluvial par classe granulométrique a été effectuée en utilisant des paramètres hydrodynamiques obtenus à partir d'un modèle 1-D du fleuve. La comparaison de cette capacité avec les valeurs de MES mesurées permet de localiser les zones en équilibre et les zones de dépôt de sédiments.

Mots clés : Transfert sédimentaire, Fleuve Niger, Sahel, Matières en suspension (MES)

Abstract

In order to achieve the overall objective of this research which was to gain an understanding into the impact of land cover change on sediment production and transport in the middle Niger River basin, the application of various approaches was necessary. These approaches included the study of hydrological data (1929 – 2008) and land cover data (1965 – 2000), in addition to the measurement of sediment characteristics (2005-2008).The study focused on two Sahelian sub-basins (the Gorouol and the Sirba basins) in comparison to a Sudanian basin (the Mékrou basin). An evaluation of the evolution of land cover by remote sensing techniques showed an increase in disturbed bare soil surfaces favouring an increase of sediment transfer to the middle Niger via conventional tributaries as well as ungauged ephemeral streams that have increased in number and size since the 1970s. Field measurements of sediment characteristics where carried out at ten locations along the middle Niger River and some of its tributaries in order to quantify the sediment flux and sources in the study area. Hydrological analyses showed the impact of the reduction of precipitation on river discharge, with the most recent dry period, resulting in the alteration of the Niger River's regime at Niamey and affecting river planform. The sediment flux analysis for the middle Niger River points to the existence of other significant sediment sources apart from the main tributaries. A simulation of the sediment transporting capacity, by grain size class, using data from a 1-D model of the river enabled the localization of areas of sediment equilibrium and deposition, when compared to measured sediment concentration values.

Keywords: Sediment transfer, River Niger, Sahel, Suspended sediment concentration (SSC)

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Symbol	Units	
D_*		Particle parameter
D_{10},D_{16} D_{84},D_{90}	µm, mm, m	Characteristic particle diameters of sediment
D_{50}	µm, mm, m	Median particle diameter of sediment
D_s		Representative size of suspended sediment
g	m/s^2	Acceleration due to gravity
h	m	Flow depth
k		von Karman's constant=0.4
k_s	m	Effective bed roughness
Q	m^3/s	River discharge
ρ	kg/m^3	Density
s		Specific density
T		Bed shear stress parameter
u_*	m/s	Bed shear velocity
w	m/s	Particle fall velocity
υ	m^2/s	Kinematic viscosity coefficient

ABN/NBA	Autorité du Bassin du Niger/Niger Basin Authority
ASTM	American Society for Testing and Materials
FAO	Food and Agricultural Organisation
GLCF	Global Land Cover Facility
IGN	Institut Géographique National
IRD	Institut de Recherche pour le Dévelopement
LGP	Laboratoire de Géographie Physique
LTHE	Laboratoire d'étude des Transferts en Hydrologie et Environnement
ORSTOM	Office de la Recherche Scientifique et Technique d'Outre-Mer
mg/l, kg/m^3	
SSC	Suspended sediment concentration

Introduction: Silting up of the middle Niger, myth or reality?

1. Problem statement

In recent times, the naturally sparse vegetation of the semi-arid West African Sahel has been adversely affected by a 25 to 30 percent reduction in precipitation as well as an increasing livestock and human influence due to overgrazing and an increasing demand for fuel wood [*M-F Courel*, 1985; *L Descroix*, 2003]. In the Sahel, the reduction in precipitation has been observed to have an amplified effect in the flows of the Niger River.

In the same period, due to more denuded soils, sediment is more easily transported into the Niger River from its basin. In addition, the Niger River's reduced flow has resulted in what has been called a silting-up of the Niger's middle basin.

2. Justification of the study

The consequences of the combination of an increased sediment supply and reduced flows in the Niger River may be numerous and varied, ranging from more extreme low flows, variable high flow patterns, to the potential silting-up of proposed hydraulic works along the river. The potential negative impacts of increased sediment input on aquatic life, river navigability, and water treatment are not negligible and has caused debate and speculation amongst scientists and basin managers as to the causes and severity of the observed phenomena thereby generating the following questions: Sediment deposits or just an exposed river bed?, less water or more sediment?

The facts have been difficult to separate from perception due to limited or non-existent direct measurements of the sediment dynamics in the study area.

The present study is therefore necessary as a contribution to the understanding of the basin's evolution in terms of sediment production, transfer, and main controlling factors during a period of rapid land use change. It may also be useful to basin managers in devising sediment control measures as well in planning hydraulic works in the basin that may be affected by sedimentation.

3. Aim of the study

The present work aims to study land cover change and its relationship with sediment production, transport, and deposition in the middle Niger River basin.

Further objectives will be to:

- Quantify changes in land cover between 1965 – 2000;
- Analyse the sediment transport within the middle Niger River basin (to understand the major transport mechanisms, constraints etc.);
- Evaluate the influence of land cover change on:
    - The sediment transport of the middle Niger River,
    - The increased sedimentation within the river;
- Determine the:
    - Predominant mode of sediment transport,
    - Sediment sources,
    - Factors controlling sediment deposition,
    - Areas of sediment deposition.

4. Research approach

The aim of the study being to understand the relationship between land cover change and sediment production as well as to study the transport of sediment in the middle Niger basin, the research was carried out in the following manner.

- Firstly, it was necessary to apply remote sensing techniques in order to gain a synoptic understanding and estimation of the land cover change that has occurred in the study area over the past few decades.
- Secondly, climatic factors, particularly precipitation and its impact on river discharge were analysed for the study area.
- Thirdly, measurements of sediment and riverbed characteristics, such as suspended sediment concentration and sediment particle size, where carried out at several locations along the middle Niger River and its tributaries with particular attention to the confluences of three tributaries (two Sahelian rivers and one Sudanian river) with the Niger River. This was with a view to quantifying tributary contribution to the middle Niger River's sediment load. In addition, the measurements were carried out in order to

understand and quantify the movement of sediment along the middle Niger River, distinguishing erosion zones from deposition zones.

The information derived from the above methods were used to evaluate the relationship of sediment production in the middle Niger River basin to land cover change and its associated effects like increased local runoff.

The major results are grouped according to research components as river form and bed evolution (part II), land cover change analysis (part III), hydrology (part IV) and sediment transport analysis (part V).

5. Funding and collaboration

In order to improve the management of the Niger River basin's resources, the Niger Basin Authority (NBA) expressed the need of gaining a better understanding of the sediment transfer dynamics especially in view of the continuing environmental changes.

The study was jointly funded by the embassy of France in Abuja, Nigeria, through a "Boursier de Gouvernement Francais" scholarship, the Niger River Basin Authority (NBA), the Institut de Recherche pour le Développement (IRD), and the Laboratoire de Transfert en Hydrologie et Environnement (LTHE) where most of the work was carried out.

This study involved fieldwork, laboratory analyses, as well as data analyses, which was made possible by the collaboration of various institutions.

In addition to providing the river discharge data used in this study, the **NBA** also complemented the logistics provided by **IRD** for the fieldwork. The centre regional **Agrhymet** provided assistance to this study in the form of satellite imagery and computing facilities. Working space for the laboratory analysis of the water/sediment samples was provided by the departments of **Geography** and **Geology** of the **Abdou Moumouni University**, Niamey as well as the genetics laboratory of **IRD** Niamey.

The Laboratoire de Géographie Physique (LGP), Paris, provided Geographic Information Systems support. The laboratory analysis of suspended sediment size characteristics, data analyses, and bibliographic research were carried out at **LTHE** Grenoble where a suitable environment for scientific collaboration was provided.

Part I – Study area and environmental context

In order to place the results obtained in the subsequent parts of this work into proper context, it is necessary to describe the environmental factors that affect the study area. The study area is viewed in the larger context of the Niger River basin, one of the world's major rivers. The environmental setting of the study area is described by a discussion of factors such as precipitation, river discharge, geology, soil, vegetation cover, and population.

Recent and continuing climatic perturbations in addition to demographic pressure make it necessary to explore some of the direct and indirect factors that affect sediment production, transport, and deposition in the study area.

This introductory part of the study aims to:

- Describe the study stretch of the Niger River;
- Describe the general climatic context of the study area as well as its present state;
- Make a synthesis of how the interplay of environmental factors like geology, soil type and variable factors like vegetation cover and demographics may affect sediment production and transport;
- Review previous sediment monitoring programmes carried out on the Niger River.

1. The Niger River

The River Niger is Africa's third largest river after the Nile and the Congo and is West Africa's principal river. Rising at an altitude of about 800 metres in the Fouta Djallon Mountains in Guinea, its active basin lies within nine West and central African countries- Benin, Burkina Faso, Cameroon, Chad, Cote d'Ivoire, Guinea, Mali, Niger and Nigeria.

Figure I- 1 locates the Niger River basin within the African continent with respect to the basins of the Nile and Congo rivers.

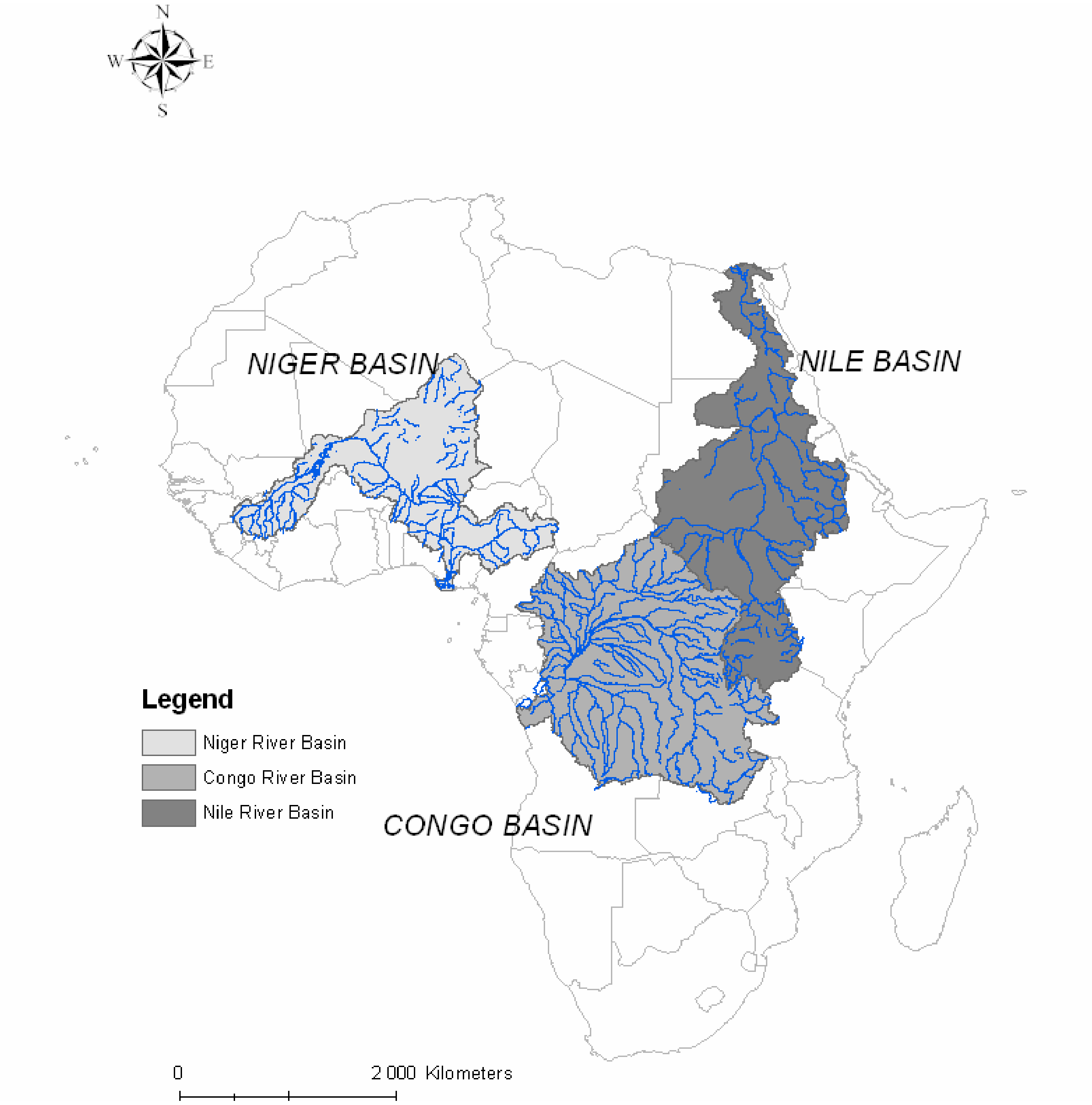

Figure I- 1 : The Niger River Basin in comparison to Africa'a major rivers

1.1. The Niger River basin

The Niger has always fascinated historians and scientists, from ancient times when it was thought to be a tributary of the River Nile, to the nineteenth century, when it was thought to empty into the River Congo. From a European point of view, Mungo Park first proved conclusively that the river flowed eastwards and Richard and John Lander were the first to map the Niger's course and to prove that it runs into the Atlantic at the Bight of Benin.

The history of the exploration and mapping of the River Niger's course is detailed in Park [1815] and NEDECO [1959] .

The full extent of the Niger's basin has been a subject of debate, because there is no input to the Niger River system from its left bank as it runs through the Republic of Niger [*I Andersen et al.*, 2005]. Its total basin area (active and inactive) is about 2.2 million km² [*A S Goudie*, 2005] while its hydrological or active basin area is estimated to be about 1.5 million km² [*I Andersen et al.*, 2005].

The Niger River basin, presented in Figure I- 2, is usually divided into four major units with different characteristics:

- The Upper Niger from its source to Ségou;
- The Inner Delta from Ségou to Tossaye;
- The Middle Niger between Tossaye and Malanville;
- The lower Niger from Malanville to the river's mouth in the gulf of Guinea.

This study focuses on the Middle Niger presented in more detail in the following section.

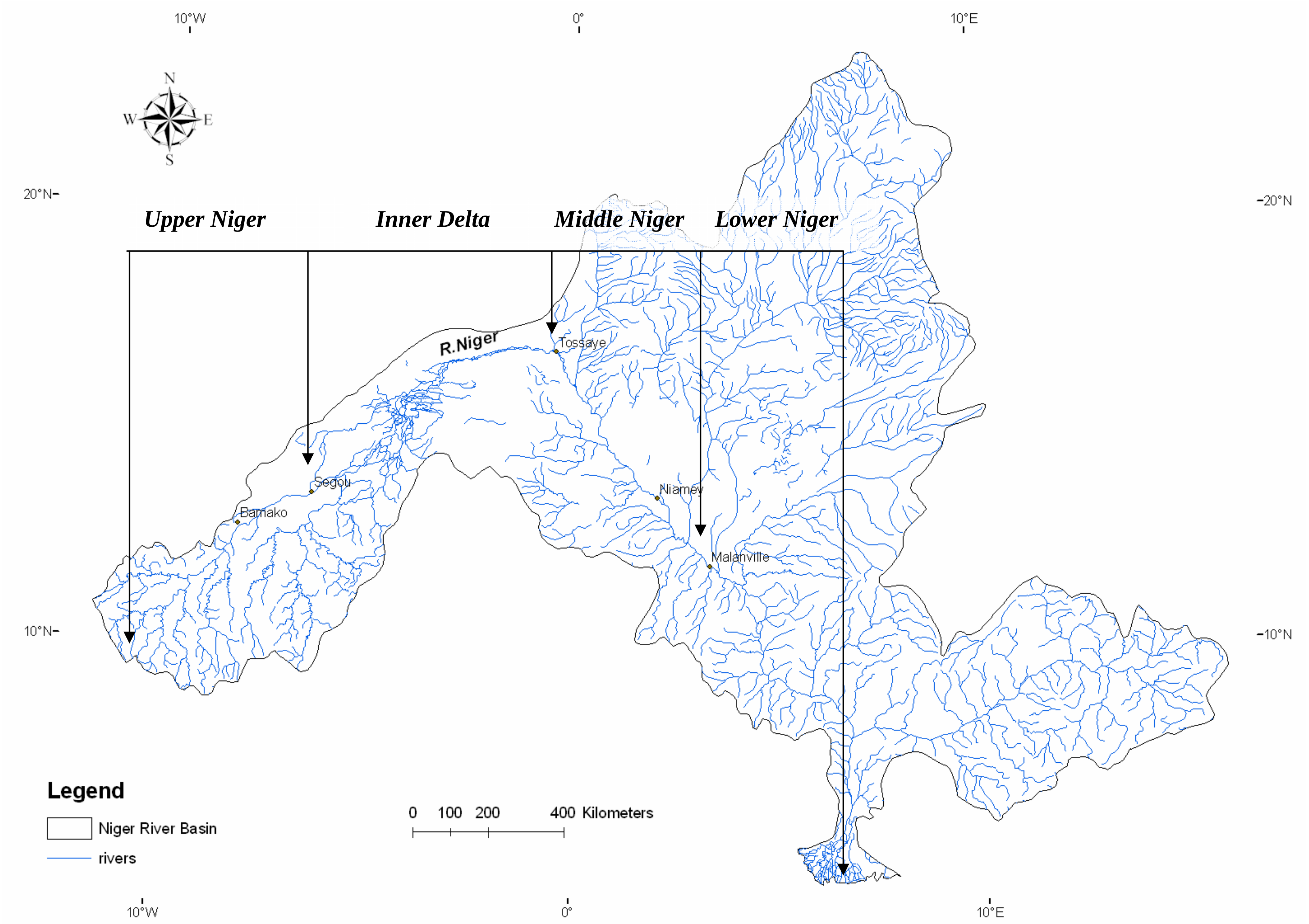

Figure I- 2 : The Niger River Basin

1.2. The middle Niger River basin

The middle Niger River is the stretch of the river just after the Niger's inner delta and up to the Niger/Benin border with Nigeria. The Niger's inner delta located in Mali is a vast area of lakes and braided streams in which large evaporation and infiltration losses occur. Between Tossaye in Mali and the Republic of Niger, the Niger River does not receive any tributaries and its discharge continues to decrease up to its confluence with its right bank tributaries beginning with the Gorouol (see Figure I- 3).

The middle Niger River receives six tributaries that originate in Burkina–Faso (Gorouol, Dargol, Sirba, Goroubi, Diamangou, and Tapoa) and three that originate in Benin (Mékrou, Alibori, and Sota). A peculiarity of the middle Niger River is that all its present day tributaries are on its right bank, its left bank having no significant tributaries. The middle section of the Niger flows in a southeasterly direction through the semi-arid Sahel region towards the more humid savannah, with a basin area located in a semi-arid to tropical climate (200-1000 mm annual rainfall).

The middle Niger is described in detail by ORSTOM [1970], Brunet-Moret et al. [1986], and Andersen et al.[2005].

1.3. Location of the study area

Within the vast middle Niger River basin, three sub-basins were selected as case studies to meet the objectives of this study. Even though the middle Niger River has eight tributaries, three of them were the focus of this study and were chosen to represent the two major climatic regions of the basin, the Sahel and the Sudan.

Two Sahelian basins for which river discharge data was largely available were therefore selected (the Gorouol and the Sirba rivers) in order to evaluate the sediment contribution of Sahelian tributaries to the middle Niger River. The Gorouol basin was of particular interest because sediment sampling had been carried out on the Gorouol at Dolbel by ORSTOM [R *Gallaire*, 1986] and because it's confluence with the Niger River is located just upstream of Kandadji, the site of a proposed dam on the Niger River.

The Mékrou basin was chosen in order to compare the Sahelian basin with the major Sudanian basin of the middle Niger River.

The magnitude of the sediment contributions of the intermediate tributaries shown in Figure I- 3 should be observable from the sediment flux measured along the middle Niger River in part V of this work.

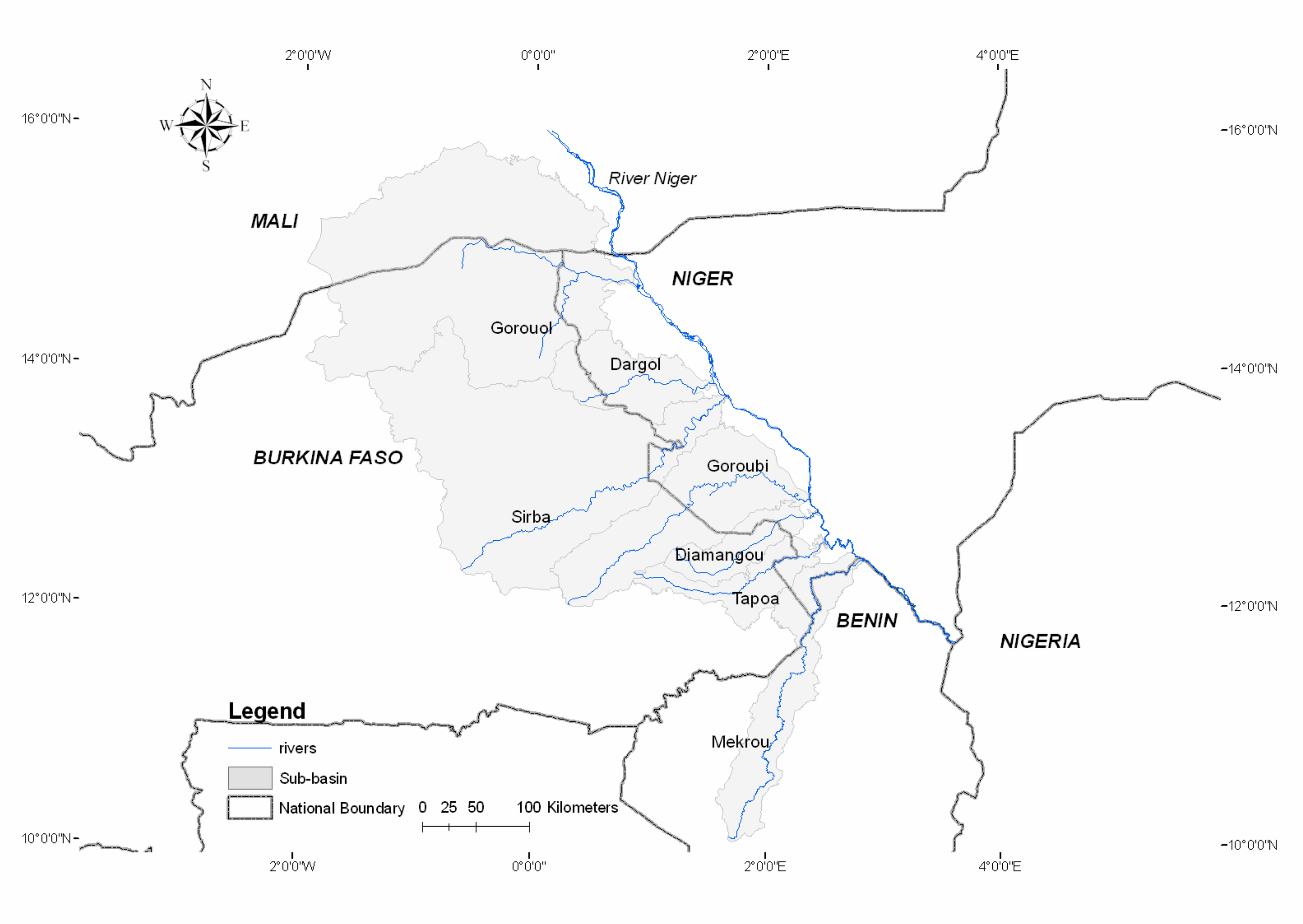

Figure I- 3 : The Study Area

1.4. The Sahel

The Sahel is the climatic zone between the Sahara desert and the savannah lands to the south. It is characterized by the strong climatic seasonality with a short rainy season and a long intensely dry season. Its exact limits have been a point of debate [*Y L'Hôte et al.*, 2003; *P Ozer et al.*, 2003].

1.4.1. Characteristics of the Sahel

The Sahel can be defined based on precipitation, as receiving 100 to 200 mm of annual rainfall at its northern limit and 500 to 600 mm of annual rainfall at its southern limit. [*A Anyamba and C J Tucker*, 2005; *A T Grove*, 1978; *H N Le Houerou*, 1980; *S E Nicholson*, 1995].

It includes much of the countries of Mauritania, Senegal, Mali, Niger, Chad, the Sudan and the northern fringes of Nigeria and Burkina Faso. Extending from approximately 12°N to 18°N, the Sahel is an ecological zone of climate and vegetation which represents a transition between the desert in the north and the more humid Savannah to the south [*H N Le Houerou*, 1980; *S E Nicholson*, 1995]. The Sahel is essentially a zone of grassland and scrubland and is sometimes defined by the length of the rainy season which ranges from about 2 months in the north to about 3 months in the south [*S E Nicholson*, 1995].

A generalized vegetation map of the Niger River basin is presented in

Figure I- 4.

1.4.2. The present state of the Sahel

Precipitation in the Sahel is characterized by a large multi-decadal variability; these large variations in rainfall have had a profound impact on vegetation dynamics in the region. The prevailing situation in the Sahel has been described by researchers and policy makers as drought [*C T Agnew and A Chappell*, 1999; *P A Jacobberger*, 1988; *Y L'Hôte et al.*, 2003; *Y L'Hôte et al.*, 2002; *E Roose*, 1996];desiccation [*M Hulme et al.*, 2001; *A Tarhule*, 2005] or even desertification [*C J Tucker et al.*, 1991].

Agnew and Warren [1996] make an important distinction in defining droughts as short periods (1-2 years) of below average moisture supply; desiccation as a process of aridisation lasting decades; and land degradation as a persistent decrease in the productivity of vegetation and soils , while desertification is a land degradation process of plant and soil resources under human impact [*H E Dregne*, 1986].

This variability in rainfall has led to a recent period of desiccation that began in the late 1960s and from which the region not yet fully recovered. While most scientists agree that the region is experiencing ongoing desiccation [*Y L'Hôte et al.*, 2002], others suggest that the rains might have recovered [*A Anyamba and C J Tucker*, 2005; *P Ozer et al.*, 2003], and yet others posit that abnormality for a region with such variability as the Sahel is a misnomer [*M Hulme*, 2001].

Below average water supply according to Dracup et al.[1980] can be described in terms of stream flow and reservoir storage for hydrologists, in terms of precipitation for meteorologists, in terms of soil moisture for agriculturists, or even in terms of a society's productivity and consumption for economists.

Available data for the Sahel (from 1905) shows a marked departure from average rainfall conditions from around 1968 to present, some parts of the region can be said to be experiencing a period of desiccation caused mainly by a reduction in precipitation as input and reduced stream flow and soil moisture as the effects or outputs.

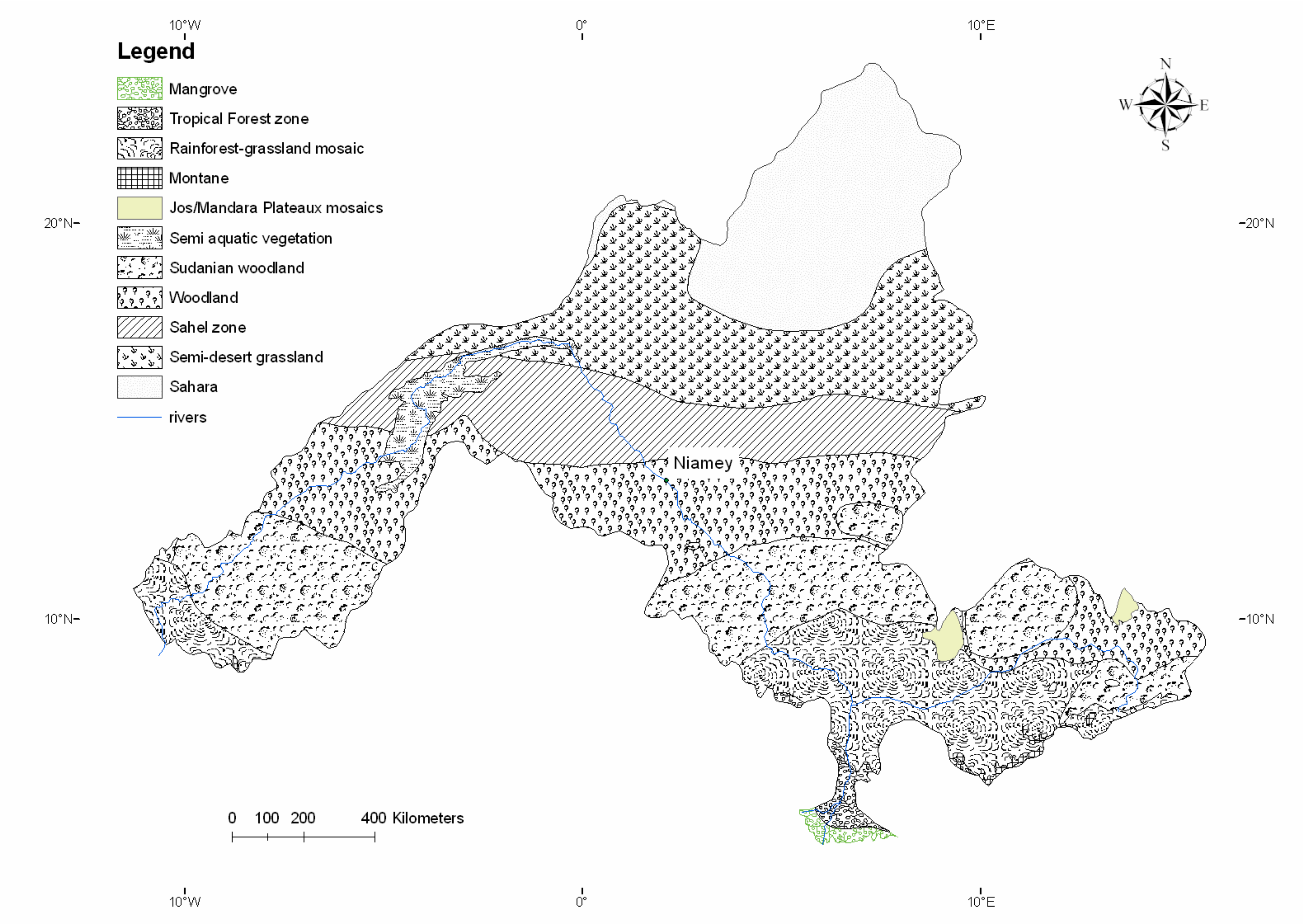

Figure I- 4 : Generalized vegetation map of the Niger River basin (after White, 1983)

2. Climate and environment of the study area

2.1. Precipitation

Average rainfall within the study area varies from 300 mm in the north to about 1000 mm in the south as the Niger River flows from the semi-arid Sahelian zone towards the wetter savannah. Data from the **Badoplu** (Base de données pluviométriques) and **EPSAT-Niger** (Estimation of precipitation by satellite-Niger) networks were used to calculate average rainfall values over the study area. A map showing the average precipitation over the study is presented in Figure I- 5.

Rainfall data for the period (1950 to 2006) from 32 rain gauge stations in the study area were obtained and used to determine the average rainfall isohyets. Where possible, only stations with continuous records were used to determine the average precipitation over the study area. The period of operation for each of the stations is detailed in Table I- 1 for the **Badoplu** data and

Table I- 2 for the **EPSAT-Niger** data.

Table I- 1: Rainfall record for the study area (Badoplu data)

Station	Start date	End date	% of complete data	Station	Start date	End date	% of complete data
Ansongo	1950	1976	89	Hombori	1950	1990	100
Aribinda	1950	1990	100	Kandi	1950	1997	100
Ayorou	1950	1990	100	Kantchari	1950	1980	100
Bani	1950	1990	100	Kolo	1950	1978	97
Banikoara	1954	1997	100	Malanville	1950	1992	98
Bilanga	1968	1990	100	Markoye	1950	1990	100
Bogande	1950	1990	100	Niamey-aero	1950	1990	100
Bouroum	1965	1990	100	Niamey ville	1950	1980	100
Dakiri	1962	1990	100	Ouallam	1950	1990	100
Diapaga	1950	1990	100	Ouatagouna	1950	1988	100
Dolbel	1959	1980	100	Say	1950	1990	100
Dori	1950	1990	100	Sebba	1956	1979	100
Gaya	1950	1990	100	Tera	1950	1980	87
Gorgadji	1950	1990	100	Tillabery	1950	1980	100
Gorom-gorom	1950	1990	100	Torodi	1950	1990	100
Gotheye	1950	1990	100	-	-	-	-

Table I- 2 : Rainfall record for the study area (EPSAT-Niger data)

Station	**Start date**	**End date**	**% of complete data**
Kolo	1990	2006	100
Niamey-aero	1991	2006	100
Niamey ville	1990	2006	100
Torodi	1991	2006	100

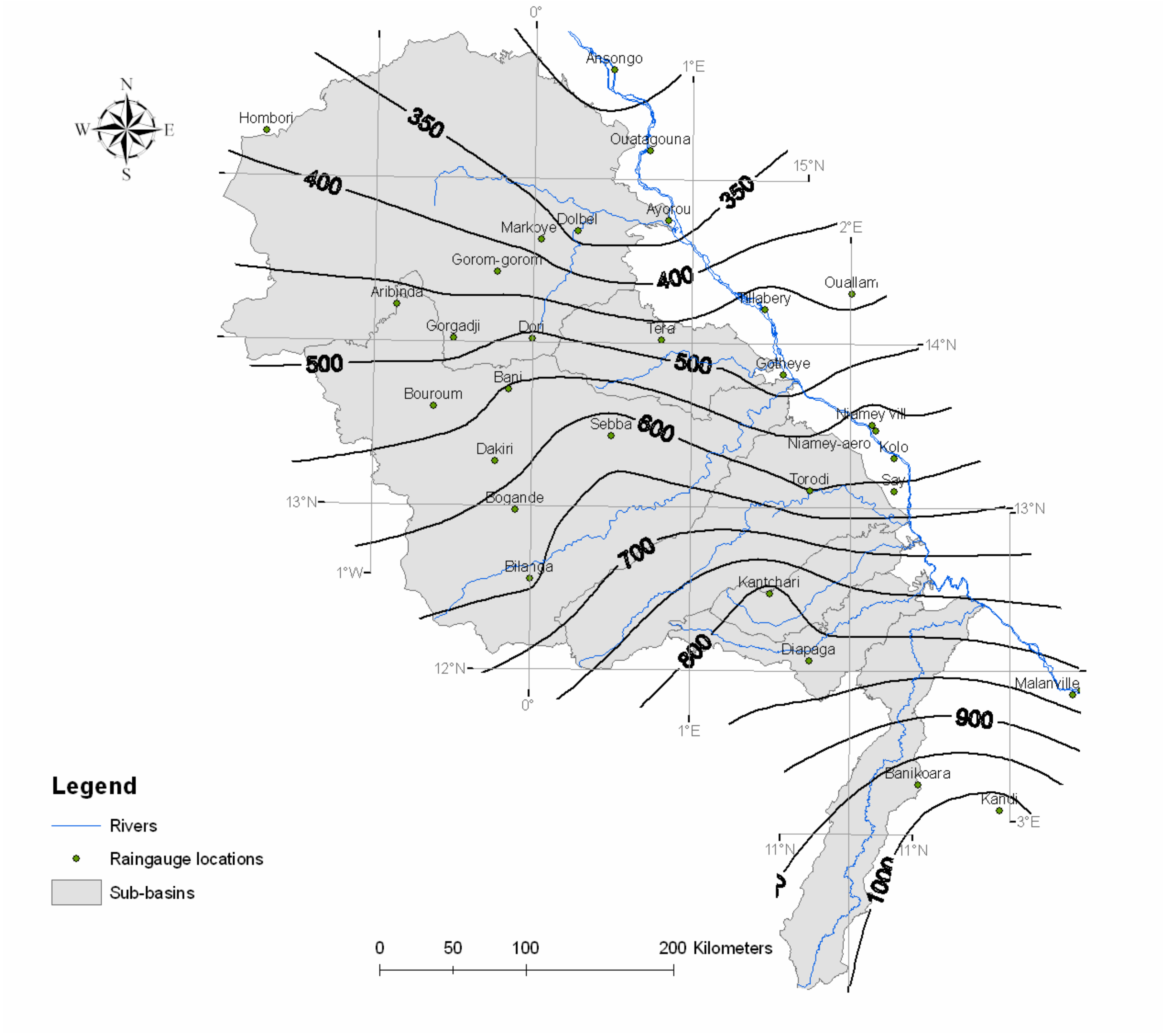

Figure I- 5 : Average rainfall over the study area 1950-2006 (*Data from Badoplu and EPSAT-Niger)*

2.2. Topography and runoff

Although the longitudinal profile of the Niger River becomes steeper as it leaves the inner delta, (see Figure I- 6) the basin of the middle Niger basin has a relatively smooth topography.

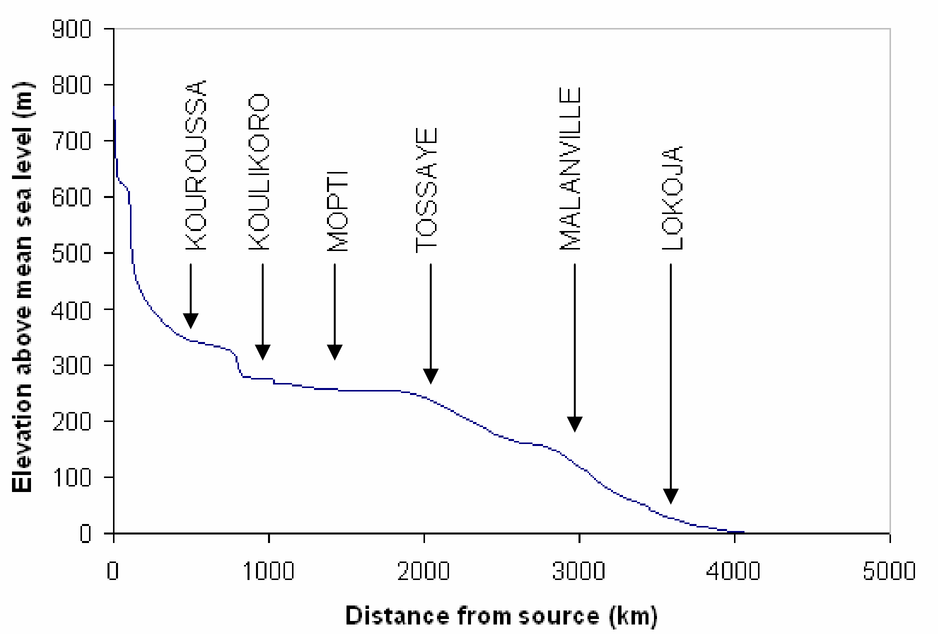

Figure I- 6 : Longitudinal profile of the Niger River (after NEDECO, 1959)

Due to the small differences in topography, concentration of flow hardly occurs and overland flow generally takes the form of sheet flow [*S M Visser et al.*, 2005].

The Niger River is the only perennial watercourse in the study area as its tributaries are more dependent on the very short local rainy season.

At Niamey, the maximum flows are usually two-fold: a first peak flow during the local rainy season and a second peak that occurs in the dry season and that is due to the delayed flood from the inland delta upstream [*I Andersen et al.*, 2005].

Desconnets et al. [1997] studied the left bank of the middle Niger River, and found that most of the runoff from precipitation ends up in pools which later infiltrate or evaporate with only about 1-2% of annual precipitation reaching the river Niger. They described the area of the middle Niger's left bank as being composed of hundreds of small hydrologic components that are rarely connected to each other, a phenomenon known as "endorheism" as opposed to "exorheism" on the middle Niger river's right bank where there are several significant seasonal tributaries .

2.3. Geology and soils

Rock lithology and soil type are important factors that affect soil erosion. Weaver [1991] indicated the existence of a strong relationship between geology and soil characteristics and noted their significance with respect to the spatial variation of soil erosion. The geological and soil characteristics of the study area are described in the following sections.

2.3.1. Geological setting of the region

The West African craton, which is the interior portion of West Africa that has been stable for about 2000Ma [*R Black*, 1985a], covers a large part of West Africa where the Niger River's basin is located. It is bounded to the east by a Neoproterozoic (1000 to 570Ma) trans-Saharan orogenic segment which is part of an over 3,000 km long linear Pan-African mobile belt that is of a sedimentary and volcanic nature [*R Caby*, 2003; *H Porada*, 1989]. This mobile belt includes the Tuareg shield to the north and the Nigerian shield to the south [*R Black*, 1985a; *N Ennih and J-P Liégeois*, 2008; *C Moreau et al.*, 1994]

2.3.1.1 Geological history of the Niger River basin

NEDECO [1959] attempted to show that before the early Pleistocene (1.6 Ma) the present day Niger River was not one but two separate river systems until the "upper Niger" (upstream of the Niger's inner delta) was captured by the lower or Nigerian Niger at Tossaye in the late Pleistocene (~10,000 years ago). This may explain the form of the longitudinal profile of the Niger River in Figure I- 6. NEDECO (1959) supported this assertion by pointing out the relatively high variation in elevation at higher altitudes of the upper Niger's basin above Koulikoro compared to the lower Niger basin and the reverse at lower altitudes.

One hypothesis of how this capture occurred proposed by Urvoy and cited in NEDECO (1959) is that at the end of the tertiary period and because of the tilting of large areas caused by subsidence and upheaval, the upper Niger drained towards the gulf of Senegal through the Senegal River. During a second phase of upheaval, either because of the formation of a sand dune barrier or because of crustal warping of the Ségou basin area, the connection between the upper Niger and the Senegal was severed with the upper Niger becoming part of the Araouane basin, a basin of internal drainage. The Tilemsi basin was divided into two separate basins, with the northern basin draining off into the Tanezruft basin and the southern branches towards the lower Niger. During a more humid period, probably ca. 75,000 years B.P, the upper Niger filled the Ségou, Timbuktu, and Araouane lakes until it overflowed the Tossaye sill, by eroding a gap in the underlying Cambrian rocks joining the Tilemsi (a now fossilized tributary of the lower Niger that joins the Niger above Ansongo). This hypothesis is illustrated in Figure I- 7 where the present day Niger basin is depicted as well as the active basin highlighted in darker blue. The shapefile for Niger river's active basin was obtained from HydroSciences Montpellier:: http://www.hydrosciences.fr/sierem/produits/index.asp?frame=datasig.

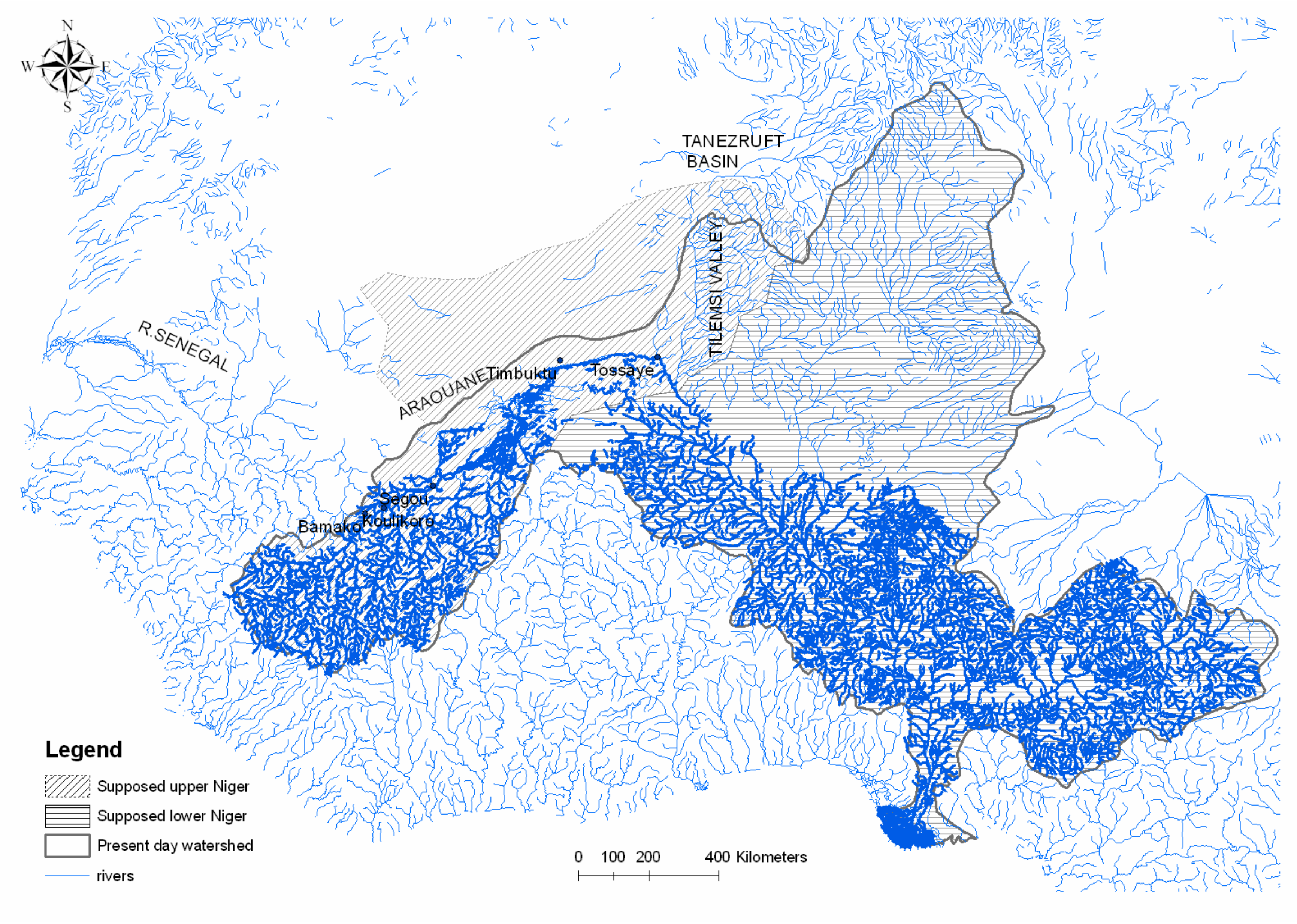

Figure I- 7 : Capture of the Upper Niger by the Tilemsi (after NEDECO 1959)

Quensière et al.[1994] questioned the possibility of the upper Niger's capture by the Tilemsi at the proposed geological timeline particularly because of the size of the gap in the Tossaye sill. Citing Beaudet et al. [1977] they posited that the magnitude of erosion present at the Tossaye sill would have required a much longer period than that between the late Pleistocene and the present (10,000 years) to occur.

An in-depth geological chronology of the study area is outside the scope of the present study but is well described by Bessoles [1977], Black [1985 a, b] and Bellion [1987].

The geological formations in the Niger River basin range from Archean to more recent alluvial deposits.

At its source in Guinea, the Niger flows over mostly Precambrian eruptive granites. Ancient schists overlain by Neogene-Palaeogene alluvial deposits mark the basin's deposition history as it traverses Guinea. For the rest of its upper course, the Niger River flows across sediments and low grade sediments of the carboniferous-Neoproterozoic period as well as dunes and laterites of the Recent-Neogene period.

2.3.1.2 The geology of the middle Niger River basin

As it bends and flows in a southeasterly direction, the Niger River in its middle section traverses the following geologic formations described below and presented in Figure I- 8:

1. Recent Neogene: As it exits the inland delta and up to Gao, the Niger traverses dunes and laterites of the recent Neogene.
2. Carboniferous- Neoproterozoic: Between Ansongo and Labezanga, the Niger River crosses a band of sediments and low-grade metasediments of the Neoproterozoic era and Carboniferous period.
3. Paleo-proterozoic: Between Labezanga and Gotheye upstream of the Sirba's confluence with the Niger, the Niger River traverses granites, gneisses, schists, migmatites and amphibolites of the Paleo-proterozoic era.
4. Neogene-Paleogene: Lacustrine and marine sediments of the Neogene to Palaeogene period are dominant as the Niger flows between Farié-Haoussa and Kirtachi. As the Niger passes through the "double V", sediments and low-grade sediments (Carboniferous-Neoproterozoic) interrupt this formation. Between Boumba and Malanville the Niger river is bounded by lacustrine and marine sediments of the Neogene-Palaeogene on its left bank and alluvial sediments of the recent Neogene period on its right bank.

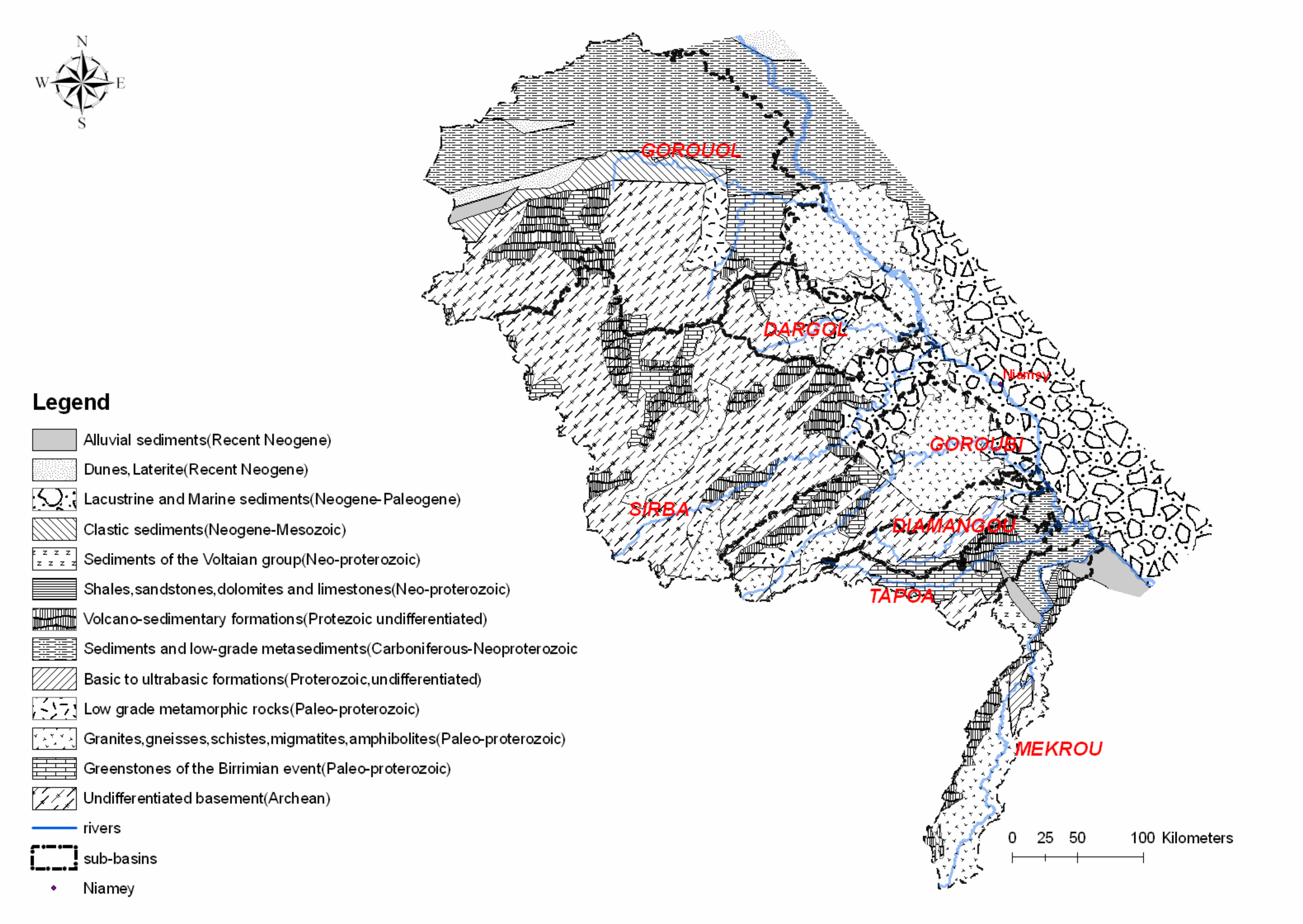

Figure I- 8: Geology of the Middle Niger basin adapted from Schlüter (2006)

Figure I- 8 shows the geological formations of the middle Niger River basin adapted from Schlüter [2006]. A large part of the middle Niger basin is undifferentiated Archean basement. The most recent formations are lacustrine sediments from the Neogene-Palaeogene period found near the Sirba's confluence with the River Niger as well as clastic sediments in the Gorouol basin. Alluvial sediments from the recent neogene are located near the Mékrou's confluence with the Niger River.

The Gorouol basin is composed mainly of the Archean basement and carboniferous sediments and metasediments, metamorphic rock formations as well as more recent dune and laterite formations.

A large proportion of the Sirba basin, especially its upper basin, is of undifferentiated Archean basement; while more recent sedimentary formations are found in its lower basin.

The Mékrou's basin is composed mainly of granites, gneisses, and schists in its upper basin and sediments and metasediments in its lower basin.

2.3.2. Soil properties

Soil properties are dependent upon climate, vegetation cover, topography, as well as parent material and weathering. The dominant soils of the study area are described using the FAO-UNESCO soil classification system. An understanding of the characteristics of the soils in the study area is necessary in order to evaluate their vulnerability to erosion.

2.3.2.1 Soils in the middle Niger River basin

Periods of drought exacerbated by wind and water erosion, as well as agricultural overuse (overgrazing, deforestation etc.) in the semi-arid Sahel is of major concern in terms of agriculture and land conservation. Knowledge of the properties and characteristics of soil is important in gaining an understanding of the study area's vulnerability to erosion.

According to the FAO [2003] soil map, the major soils of the middle Niger River basin include the following as described by Driessen et al. [2001]

- Arenosols, which are correlated to the French classification system as "classe des sols minéraux bruts" and "classe des sols peu évolués" are siliceous and calcareous sands that occur in arid to humid climates and in sandy plains under mostly sparse and/or grassy vegetation. In semi-arid areas like the Sahel, they are associated with areas of shifting sand dunes. They tend to be weakly structured and their top soils are liable to water and wind erosion.

- Cambic Arenosols have a genetically young subsurface horizon showing evidence of alteration relative to underlying horizons, such as modified colour or removal of carbonates.
- Luvic Arenosols have a subsurface horizon having distinctly more clay than the overlying horizon because of illuvial transfer of clay and/or destruction or selective erosion of clay in the surface soil.

- Luvisols (sols lessivés) are characterized by clay mobilization in their top soils and are susceptible to structural degradation. They are a source of particulate clay transfer to surface waters.
  - Ferric Luvisols have a subsurface horizon in which segregation of iron has occurred to the extent that large mottles or concretions have formed in a matrix that is largely depleted of iron.
  - Gleyic Luvisols are those that show visible evidence of prolonged water logging by shallow groundwater.
  - Plinthic Luvisols possess a subsurface horizon consisting of an iron-rich, humus-poor mixture of kaolinitic clay with quartz, which changes irreversibly to a hardpan or to irregular aggregates on exposure to repeated wetting and drying.
- Regosols, known in the French classification as "Sols peu évolués régosoliques d'érosion" or "Sols minéraux bruts d'apport éolien ou volcanique", are common in eroding lands and particularly in arid or semi-arid areas or mountain regions. Many Regosols form a hard surface crust early in the dry season and hinder the emergence of seedlings and infiltration of rain in the wet season.
  - Eutric Regosols are Regosols with 50% or more base saturation.
  - Dystric Regosols are low base soils.
- Planosols, from the latin *planus* or flat, are soils with a degraded eluvial surface horizon abruptly over dense subsoil that are subject to water saturation in wet periods because of stagnation of rain or flood water.
  - Solodic Planosols are soils formed in arid or semi-arid areas where more soils are input at the soils surface than can be removed by leaching. They have an acidic subsurface horizon over a hard compact underlying horizon.
- Lithosols, also known as Leptosols, are genetically young soils with no clearly expressed soil morphology and consisting of freshly and imperfectly weathered rock or rock fragments. They are generally free-draining soils that may have groundwater at shallow depth.

- Vertisols are heavy clay soils with a high proportion of swelling. The name Vertisols from the Latin *vertere,* to turn, refers to the constant internal turnover of soil materials. They occur in depressions and level to undulating areas with an alternation of distinct dry and wet seasons.
  - Chromic Vertisols are Vertisols with a reddish colour.
- Cambisols, also known as "sols bruns" in the French classification, that show a beginning of horizon differentiation evident from changes in colour, and in semi-arid regions are found in young deposition areas as well as in erosion areas after mature soils have been eroded.
  - Eutric Cambisols are soils with 50% or more base saturation.
  - Vertic Cambisols are Cambisols with a subsurface horizon rich in expanding clays.

A generalized soil map of the study area is presented in Figure I- 9.

Luvic Arenosols are the major soil group along the middle Niger River with a band of Eutric Cambisols around the area of the Gorouol-Niger confluence.

Eutric Regosols described above, are the dominant soil in the Gorouol and Sirba basins. The other major soils of the Gorouol basin are Luvic Arenosols and Cambic Arenosols. The southern part of the Gorouol basin has areas of Solodic Planosols. Cambisols, Gleyic Luvisols and Chromic Vertisols.

The other major soils of the Sirba basin include Luvisols, Arenosols, and some areas of Planosols.

The soils in the Mékrou basin are mainly Ferric Luvisols, with some areas of Regosols and other Luvisols.

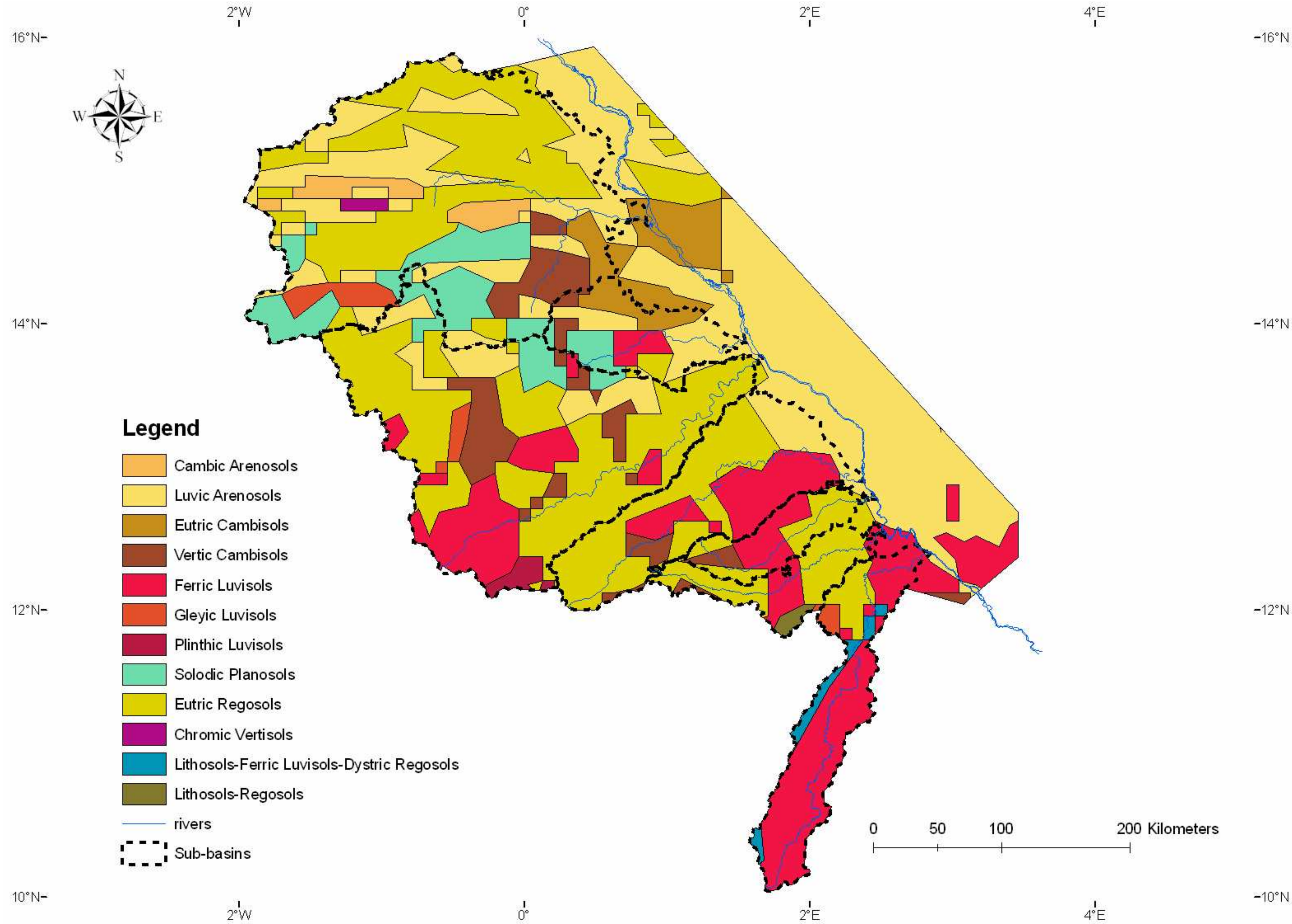

Figure I- 9: Generalized soil map of the study area

2.3.2.2 Vulnerability of soils to erosion

Erosion is a natural process of soil loss that involves the detachment and removal of rock particles by water and wind action. Geologic or normal erosion is the erosion of the earth's surface under natural or undisturbed conditions and is described by Roose [1996] as the slow shaping of hillsides (0.1 to 1 t/ha/yr), while accelerated erosion due to human activity is 100 or 1000 times faster than normal erosion, usually between 10 to 700 t/ha/yr.

Diallo [2000] studied the erosion characteristics of soils on 100 m² experimental plots in the Djitiko basin, Mali (a sub-basin of the Upper Niger River). Diallo [2000] found the *sols ferrugineux* (Lixisols[1]) and *sol brun* (Cambisols) to be the most affected by changes in soil cover (from a fallow state to a bare soil state) in terms of runoff as depicted in Figure I- 10. In terms of erosion, the same two soils were the most susceptible to water erosion when changed from fallow to bare soil as shown in Figure I- 11.

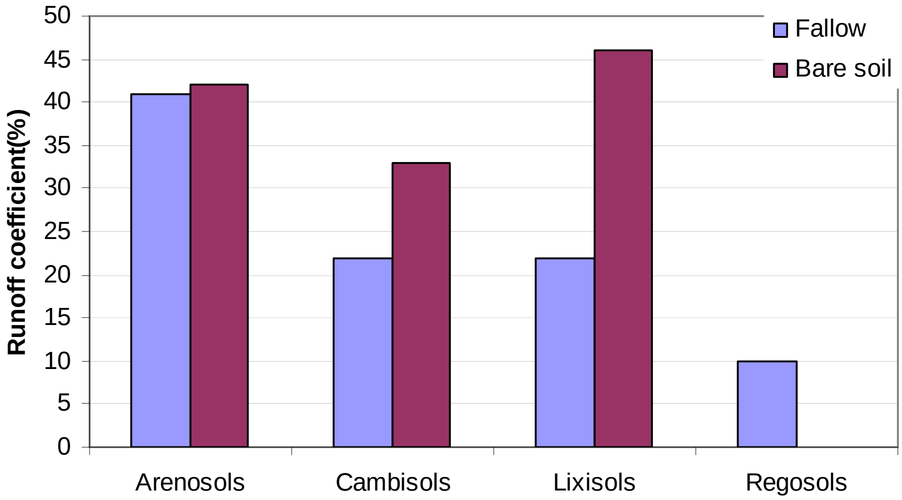

Figure I- 10: Runoff coefficients of some soils(adapted from Diallo [2000]

[1] Lixisols are known to be particularly prone to erosion when exposed to the direct impact of raindrops (Driessen et al. 2001).

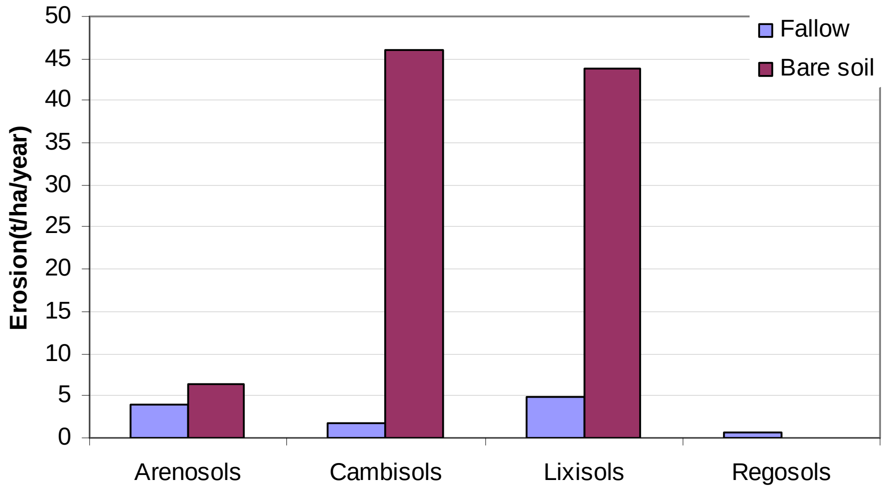

Figure I- 11: Estimated rate of erosion of some soils(adapted from Diallo [2000]

Casenave and Valentin [1989] suggested that in addition to soil type and perhaps more importantly, the infiltration and runoff characteristics of soils are dependent upon "soil surface features". They defined the soil surface features in terms of soil porosity, faunal activity (the presence of termites and earthworms) and the percentage of large soil particles (>2 mm) in the 0 - 20 cm horizon.

Using rainfall simulation experiments Casenave and Valentin [1989] studied the behaviour of different types of cultivated and non cultivated soils and reached the conclusion that surface crusting was the major factor controlling infiltration and runoff on Sahelian soils. They found uncultivated soils, with crusted surfaces with less than 20% earthworm activity to have the lowest rates of infiltration and the highest runoff coefficients. Although their experiments did not test soil types such as Arenosols and Vertisols, they estimated that these soils would have very low infiltration rates and relatively high runoff coefficients.

2.4. Vegetation

Vegetative cover influences soil erosion dynamics by protecting the soil surface from raindrop impact, maintaining or enhancing soil infiltration capacity, holding soil particles in place and reducing runoff velocity [*B J Fu et al.*, 2005] .Vegetation clearance on the other hand has been known to increase erosion or sediment production by an order of magnitude or more [*D E Walling*, 1999].

The Sahelian landscape supports mainly wooded vegetation (typically between 1.5 and 4 metres tall) and grassland.

The chief woody species are acacias such as Acacia tortilis as well as A. laeta, Commiphora Africana, Balanites aegypticiaca. The density of the larger woody plants is variable and largely dependent upon water supply and the amount of human interference [*F White*, 1983] and form a pattern of alternating vegetated stripes and bare areas also known as "tiger bush" [*S Galle et al.*, 1999]

The grass is more or less continuous and is usually not more than 60 cm tall consisting of mostly of annual species like Cenchrus biflorus, Schoenefeldia gracilis, Aristida stipoides and Tragus racemosus,. Grasses are replaced by annual weed such as Boerhavia coccinea and Tribulus terrestris in heavily grazed and trampled areas [*F White*, 1983].

The northern limit of Cenchrus biflorus an annual grass is often regarded as the southern border of the Sahara, while Faidherbia albida, Adansonia digitata (Baobab) and Vittelaria paradoxa (Shea tree) are found in the Southern part of the Sahel and the Sudan savannah. The density of vegetation cover is the major difference between the Sahel and the Sudan regions [*M Loireau*, 1998].

Sahelian flora are described and discussed in detail in White [1983] and Courel [1985]

2.5. The human influence on land cover in the study area

Human activities such as urbanization, land use for agriculture, and livestock grazing increase the potential for soil erosion because they alter the natural soil surface properties. According to Wilkinson and McElroy [2007] human activity has outstripped geologic processes such as rock uplift and denudation of orogenic belts as the most important continental surface changing factor.

In the study area, population growth is the driving force behind land use change. The average annual rate of population change for the four countries in which the middle basin of the Niger River is located (i.e. Benin, Burkina-Faso, Mali and Niger), ranged from 2.98% to 3.52% for the period between 2000 and 2005. The United Nations population division forecasts that between 2005 and 2010, Niger followed by Mali will have the highest rate of natural population increase [*United Nations*, 2007].

A comparative plot of population growth for the four countries showing the rapid population growth of the Niger Republic is presented in Figure I- 12 with data from United Nations Population Division's population database [*United Nations Population Division*, 2006].

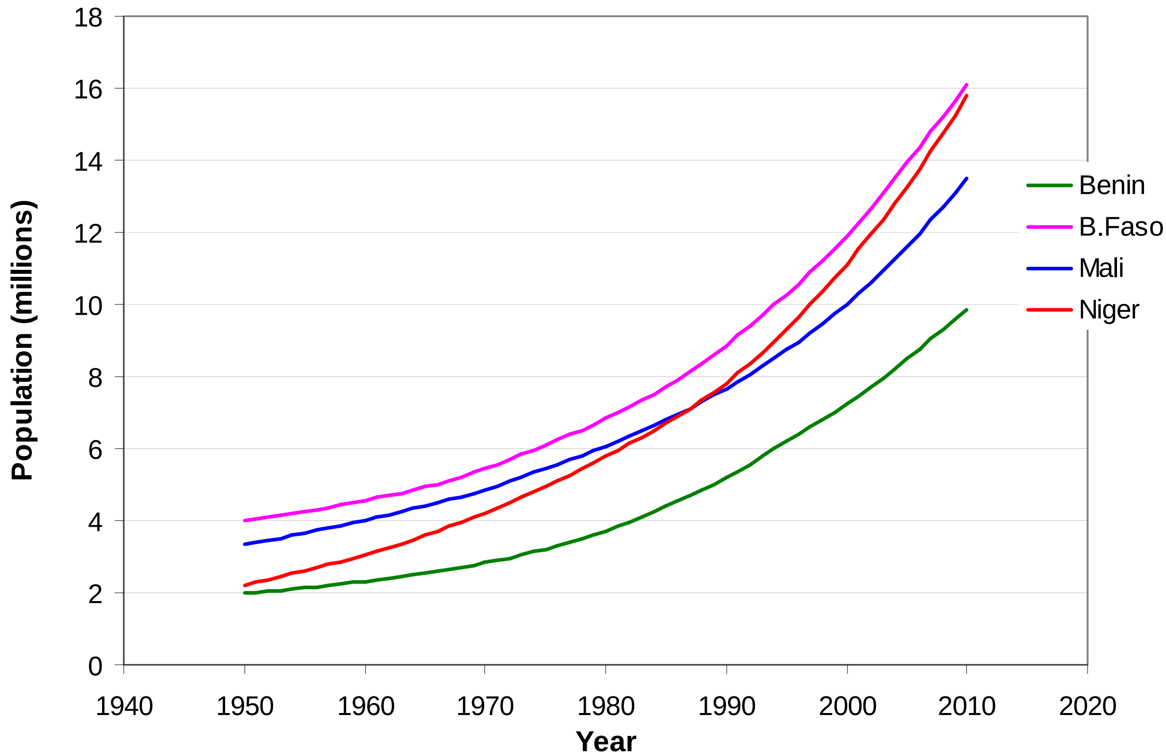

Figure I- 12: Population estimates/projections for the middle Niger basin countries (1950-2010)

Dolman et al. [1997] inferred that such local influences along with external forces like regional climatic conditions may be responsible for the reduction in vegetation and rainfall leading to sometimes permanent degradation of the land surface in the Sahel.

The demographic pressure on the region is accentuated by the fact that around 90 %[2] of the Sahelian population of the study area is dependent on agriculture for their livelihoods [*FAO*, 2008a] and firewood is widely used for cooking. In the Sahelian areas of the study area, the natural vegetation cover has steadily given way to millet fields. According to the Statistics division of the Food and Agricultural Organization [*FAO*, 2008a] the area of land harvested for the total of cereals, roots and tubers and vegetables in Niger, for instance, has more than tripled[3] since 1961 (see Figure I- 13a).

Figure I- 13a shows the evolution of cultivated land for the countries of the middle Niger basin, while Figure I- 13b presents cultivated land as a percentage of each country's total agricultural area.

Figure I- 13a and Figure I- 13b show that there is only a slight increase in the evolution of the area of cultivated land in the other three countries compared to Niger. A slight decrease in cultivated area as a percentage of the total cultivable area was observed for Benin.

[2] See Table A1 in appendix A for data
[3] See Table A2 in appendix A for data

According to Foley et al. [1997] reports up to 1989 had estimated fuel wood consumption to be between 0.6 and 0.8 kilogram/head/day with an estimated average potential woodland productivity of about 315 kilograms/hectare/year.

The widespread used of firewood for cooking is another reason for the clearing of natural vegetation. Foley et al. [1997] citing two studies carried out in 1984 and 1990 indicated that the fuel wood consumption in Niamey was 110,000 and 133,000 tonnes per annum respectively, highlighting the increasing wood consumption.

a)

b)

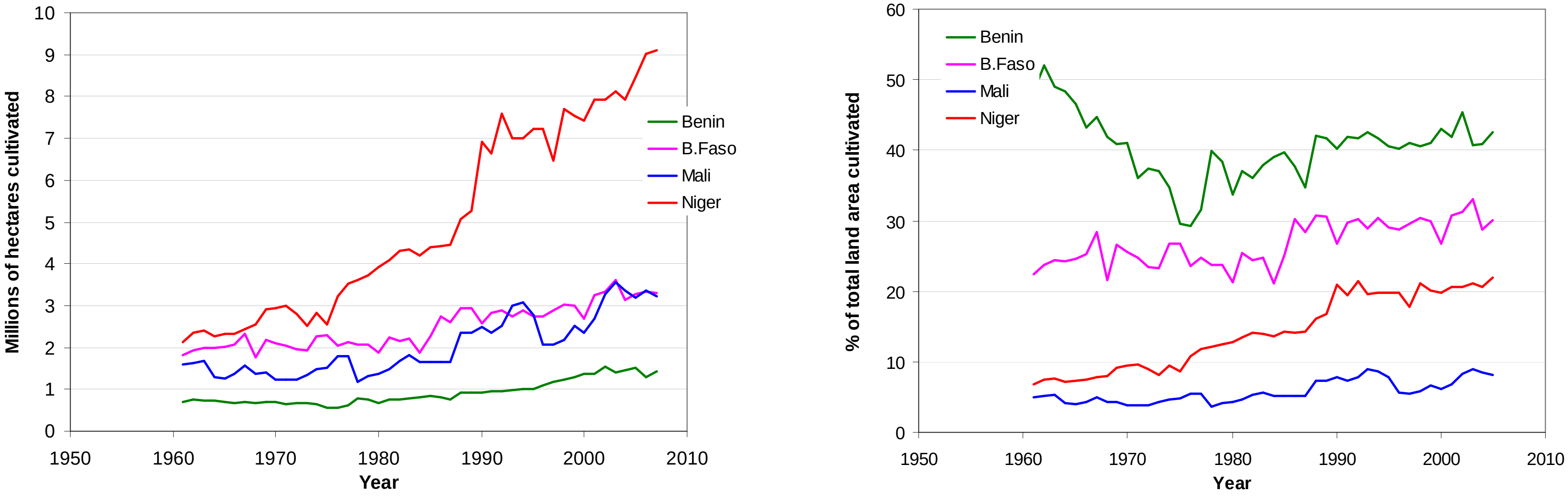

Figure I- 13: Evolution of cultivated land in middle Niger basin countries (1961 to 2007)

3. Studying the transport of sediment in the River Niger

Syvitski et al. [2005] estimated that global seasonal sediment fluxes have increased by 2.3 ± 0.6 billion tons/year through soil erosion under human influence.

Several studies have sought to understand or quantify the impact of land use or land cover change on basin-scale fluvial sediment dynamics in various circumstances and using various methods. It is widely accepted that vegetation cover affects river sediment transport because it affects runoff as well as the rate of erosion with the amount of vegetation cover and runoff production being inversely related.

3.1. The transport of sediment

Sediment and its transport in streams and rivers are studied in order to draw information not just on sediment transfer but also on the erosion and deposition processes under given hydraulic conditions as well as the possible effects of these processes on the environment.

Variations in stream and sediment transport characteristics such as the mode of transport, sediment supply or availability, river discharge, and turbulence make the measurement of sediment load extremely complex.

Sediment load in rivers can be subdivided by source as washload and bed material load or by mode of transport as suspended sediment and bedload. By source, washload is sediment transported from upland sources, while bed material load is sediment derived from denudation of the riverbed. By mode of transport, the suspended sediment is that portion that is dispersed and carried in suspension by flow turbulence and is usually comprised of the clay, silt, and fine sand fractions of sediment. Most of the washload and the finer fractions of the bed material load are transported in suspension. The bed load is that fraction of the total load that is almost continually in contact with the riverbed and is transported by sliding, rolling, or saltation by the shear stress of the water flow acting on the riverbed.

The variations that can exist from one point to another within a river system make it impractical to expect to be able to continuously measure sediment load everywhere within the system. According to Hicks and Gomez [2003], it is therefore the sampling of these variations in a river system that provide an insight to the sediment load being transported within the system. Techniques for the measurement of sediment transport are discussed further in parts III and V.

3.2. Previous regional sediment measurement efforts

Grove[1972] citing Gallais reported that semi-monthly suspended sediment measurements on the Upper Niger River were carried out at Koulikoro as far back as 1923 with concentration values that ranged from 107 mg/l in July, 50 mg/l at peak discharge and less than 40 mg/l in the dry season. Picouet [1999] reported that a weekly measurement program on a stretch of the Upper Niger River up to the Niger's inland delta between 1991 and 1997 produced similar concentration values that ranged from 0.1 to 82 mg/l at Banankoro, from 0.8 to 88 mg/l at Koulikoro and from 1.5 to 213 mg/l at Ké-Macina. Figure I- 14 indicates where these measurements were made as well as measurement locations on the middle and lower parts of the Niger basin.

The earliest sediment concentration measurements for the middle Niger basin were probably those conducted between 1976 and 1982 by "Office de la Recherche Scientifique et Technique d'Outre-Mer" **ORSTOM** for the feasibility study of a proposed dam on the Niger River at Kandadji. The study involved the measurement of suspended sediment concentration at Kandadji and Niamey on the Niger River and at Dolbel on Gorouol River. Measurements were made at three-day intervals. The observed values for suspended sediment concentration ranged from 2 mg/l to 1600 mg/l at Kandadji on the Niger River and between 94 mg/l and 5940 mg/l at Dolbel on the Gorouol River.

In the lower Niger, at 14 stations between Jebba and Aboh in Nigeria, the NEDECO study [*NEDECO*, 1959] obtained suspended sediment concentrations between 50 and 510 mg/l in a data sample of 72 infrequent measurements between 1956 and 1958. It is worth noting that the majority of observations were carried out in the dry season, while the observed maximum concentration of 510 mg/l at Kelebe occurring in August (rainy season) compared to 80 mg/l observed at the same station in November, indicating that higher concentrations may have occurred during the rainy season at the other stations. These results illustrate the importance of sampling frequency in the quantification of sediment transport.

Although the sediment concentration values were measured at different periods, it can be noted from the foregoing that the sediment concentration measured on the Niger River increases in a downstream direction with the largest observed variation occurring at Kandadji in the Niger's middle basin. The observed sediment load carried by this stretch of the Niger River combined with reducing river discharge makes it important to study the sediment transfer dynamics of the middle Niger River basin. The sediment measurement and transfer dynamics are discussed in more detail in part V of this work.

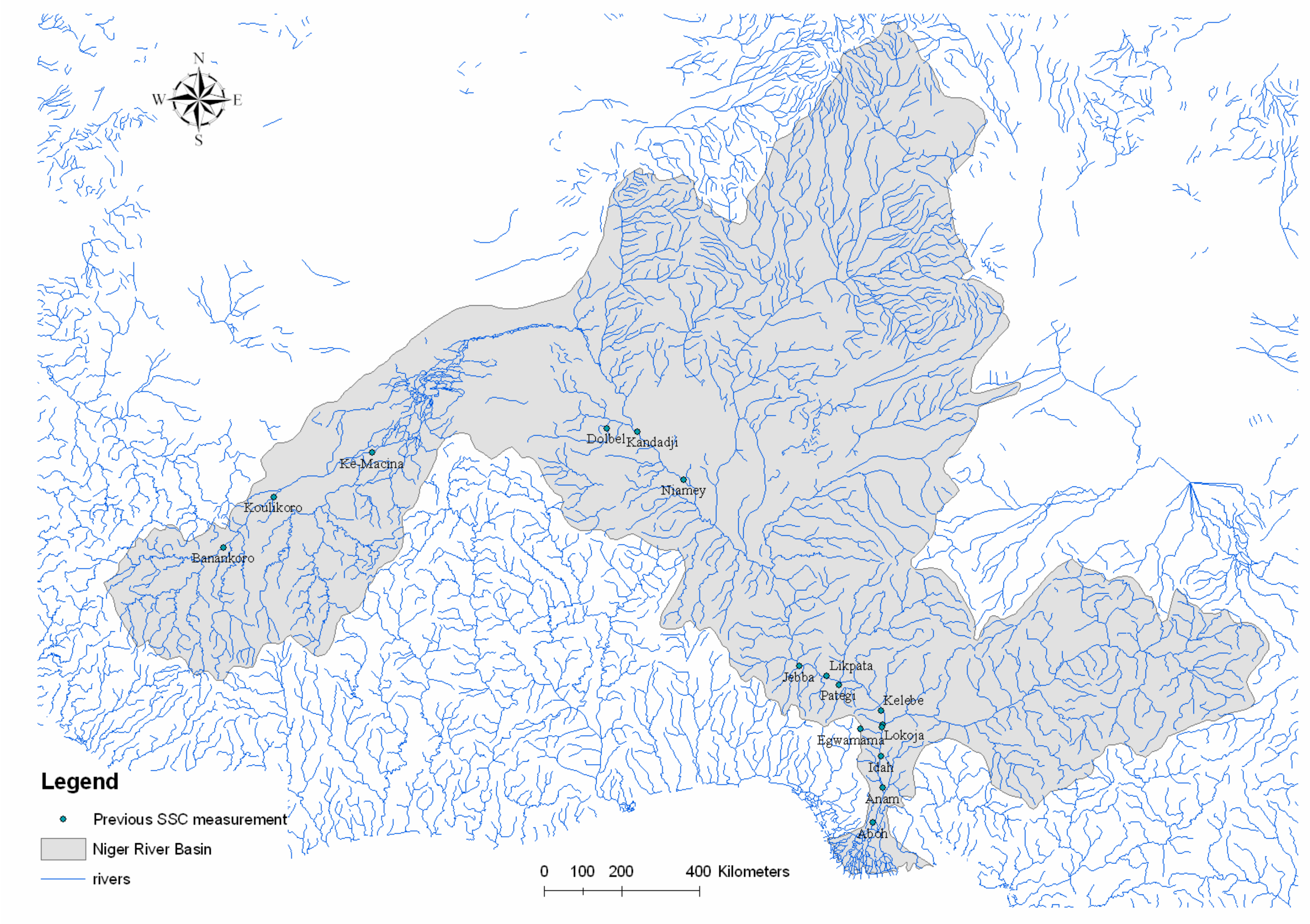

Figure I- 14: Location of previous sediment measurements in the Niger River Basin.

4. Conclusion

The study area and its climatic and environmental context have been described in the introductory part of this study.

- The soils in the study area are essentially a product of the region's geological history. A review of the soils in the area shows that:
  - The soils of the study area are susceptible to wind and water erosion. In addition, soils that represent young deposits are found along the middle Niger River.
  - The major soil type in the Gorouol and Sirba basins is one that is typical of eroding lands, and in which surface crusting occurs, hindering infiltration and possibly increasing runoff when the soils are bare. Other major soil types are weakly structured and are liable to wind and water erosion.
  - In the Mékrou basin, the major soil type is one that favours clay particle transfer from the surface horizon to watercourses.
- The study area is under strong demographic pressure with a rapidly increasing population that is dependent on agriculture as a means of livelihood, and firewood as an energy source.
- Previous sediment measurement programs on the Niger River show a trend of increasing sediment concentration as the Niger flows from its source towards the study area.

Part II - River form and bed evolution of the Middle Niger River

Most alluvial rivers are dynamic and are continually self-adjusting to naturally occurring climatic or human-induced changes. These self-adjustment processes are primarily vertical or lateral in nature [*S A Schumm*]. Channel form changes include scour or deposition, as well as channel migration, channel widening or contraction and according to Montgomery and Buffington [1997] mainly reflect changes in river discharge and sediment input. Extreme river channel changes frequently have negative consequences for navigation, the aquatic ecosystem and increase the risk of flooding.

This part of the study aims to:

- Examine the nature of medium-term (20 – 35 years) channel planform change for three reaches of the middle Niger River using a series of multi-temporal satellite imagery.
- Explore the relationship between observed channel changes to river discharge, human influences, and other factors.
- Measure possible sediment sources and erosion patterns in the middle Niger River basin
- Determine the long-term change in erosion and accretion patterns by comparing riverbed level data from a previous survey to recently measured riverbed levels for some portions of the study area.

1. River plan form change

Alluvial channel patterns can be largely explained on the basis of in-channel flow resistance and sediment transport dynamics combined with the external factors imposed on the reach by the river's physical environment such as valley slope and width as well as boundary conditions like bank strength [*H Q Huang and G C Nanson*, 2007].

Alluvial river channel patterns are the result of continual processes of self-adjustment and include straight, meandering, braiding and anabranching types.

1.1. Data

Landsat images from 1973 to 1999 of the three study reaches were acquired from **Agrhymet** and the Global Land Cover Facility, GLCF. The images were chosen to cover four periods where possible, the 1973-1979 period (the earliest available Landsat images), 1984, the 1989-1992 period, and 1999. The three reaches of the middle Niger River were chosen with particular attention to the three tributaries under consideration for this study (The Gorouol, Sirba and Mékrou rivers) in order to contrast patterns of change that may be related to these tributaries

The three reaches considered in this analysis have distinct characteristics; they are described below and represented in Figure II- 1.

- **Reach 1** is about 115 km long and comprises the Gorouol-Niger confluence. Landsat images from 1979, 1984, 1992, and 1999 were analysed for this reach. The major distinguishing feature of the Niger River in reach 1 is its complex anabranching form particularly near the Gorouol-Niger confluence.
- **Reach 2** is a 150 km long stretch that includes the Sirba-Niger confluence, starting after the Dargol-Niger confluence, and extends up to the town of Say. Landsat images from 1975, 1984, 1989, and 1999 were analysed. A Corona[4] image mosaic covering a smaller portion of reach 2 was also analysed and compared to the 1975 and 1999 images. Reach 2 can be described as a mainly braided stretch of the Niger with a lesser degree of anabranching occurring around the Sirba-Niger confluence and near Niamey.
- **Reach 3** is a 100 km stretch that includes the Mékrou-Niger confluence starting above Kirtachi and ending a few kilometres beyond Boumba and the Dallol Bosso. This reach also includes the Tapoa-Niger confluence. Landsat images from 1973, 1984, and 1999

[4] The image processing for the Corona imagery is discussed in part III

were available for comparison. The area common to all three images is compared but in addition, a comparison between the 1984 and 1999 images covering a larger river length is presented.

Reach 3 includes the "double V" section of the Niger River, has a few anabranches, and is relatively straight after Boumba.

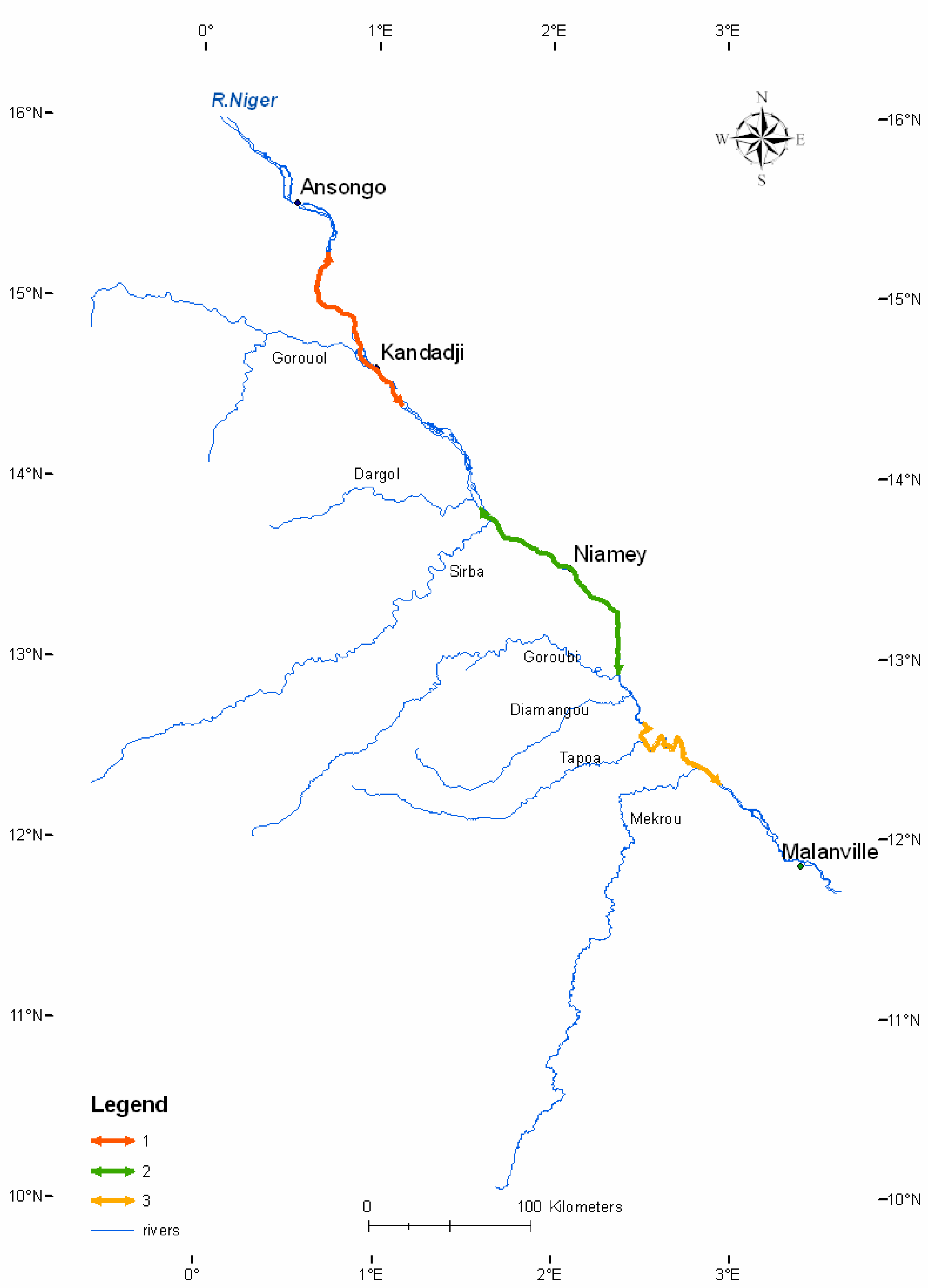

Figure II- 1: The middle Niger River and the study reaches

A series of near anniversary Landsat images and a Corona image mosaic were used to compare the changes in river planform between the 1965 and 1999 for 3 reaches of the middle Niger River. A summary of the satellite images used in the analysis as well as discharge data at some representative discharge measurement stations on the image dates are presented in Table II- 1.

Table II- 1 : Satellite imagery and discharge data for the study reaches

Reach	Image date	Path/row	Pixel size(m)	Discharge (m3/s) at gauging station			
				Ansongo	Kandadji	Niamey	Malanville
1	29/11/1979	208/050	57	1840	1840	1800	-
	05/11/1984	194/050	28.5	1060	N/A	1030	-
	18/10/1992	194/050	28.5	1270	1180	1000	-
	22/10/1999	194/050	28.5	N/A	1430	1300	-
2	13/10/1965*	N/A	N/A	-	-	1460	1740
	22/11/1975	207/051	57	-	-	1650	1570
	14/11/1984	193/051	28.5	-	-	1050	N/A
	20/11/1989	193/051	28.5	-	-	1220	1140
	31/10/1999	193/051	28.5	-	-	1370	1490
3	29/09/1973	206/051	57	-	-	1030	1230
	07/11/1984	192/051	28.5	-	-	1040	N/A
	09/11/1999	192/051	28.5	-	-	1460	1420

* CORONA satellite image DS 1025-2122DF (049 to 052)

Outlines of the three study reaches are presented in Figure II- 2 to Figure II- 4.

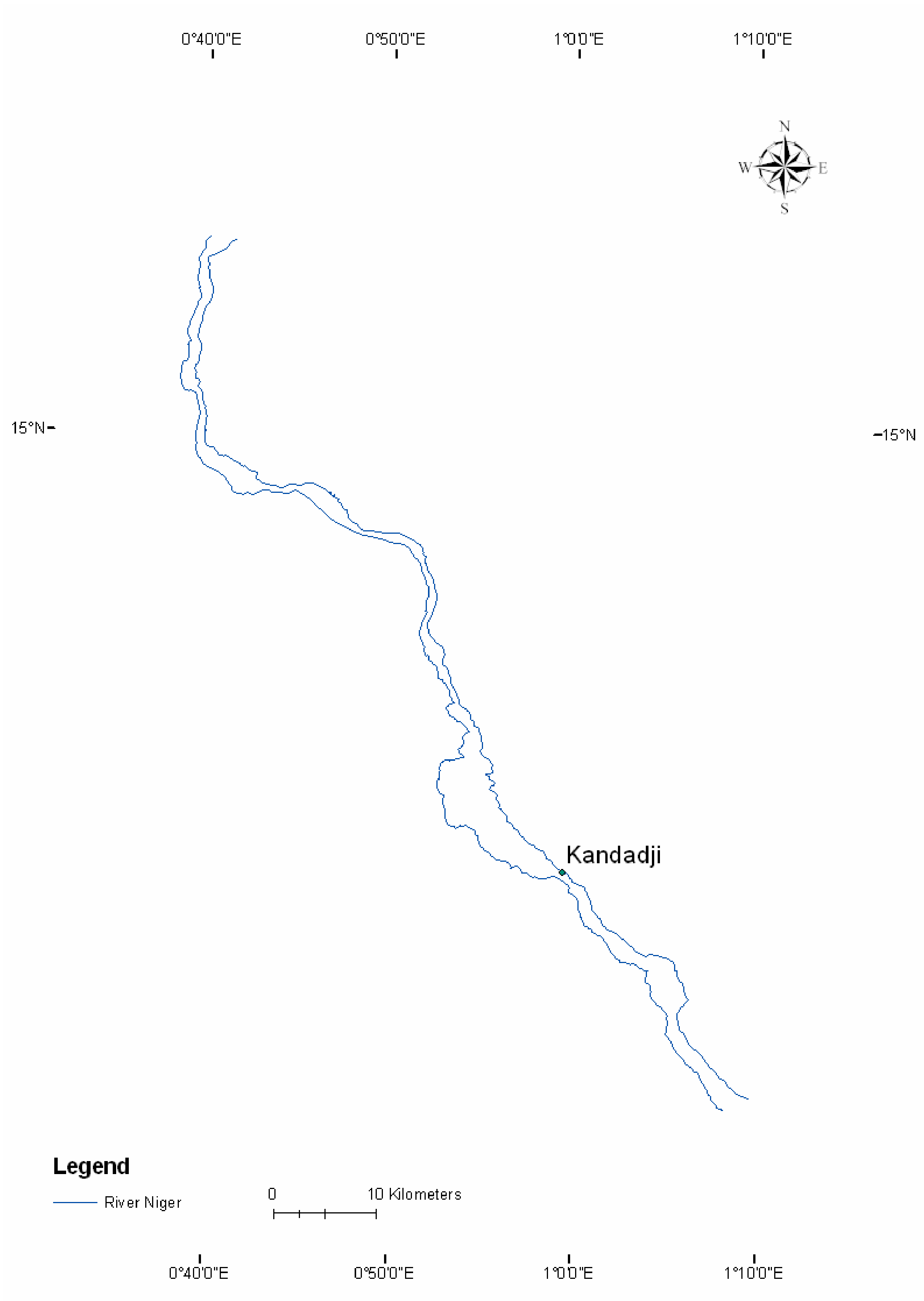

Figure II- 2: Reach 1

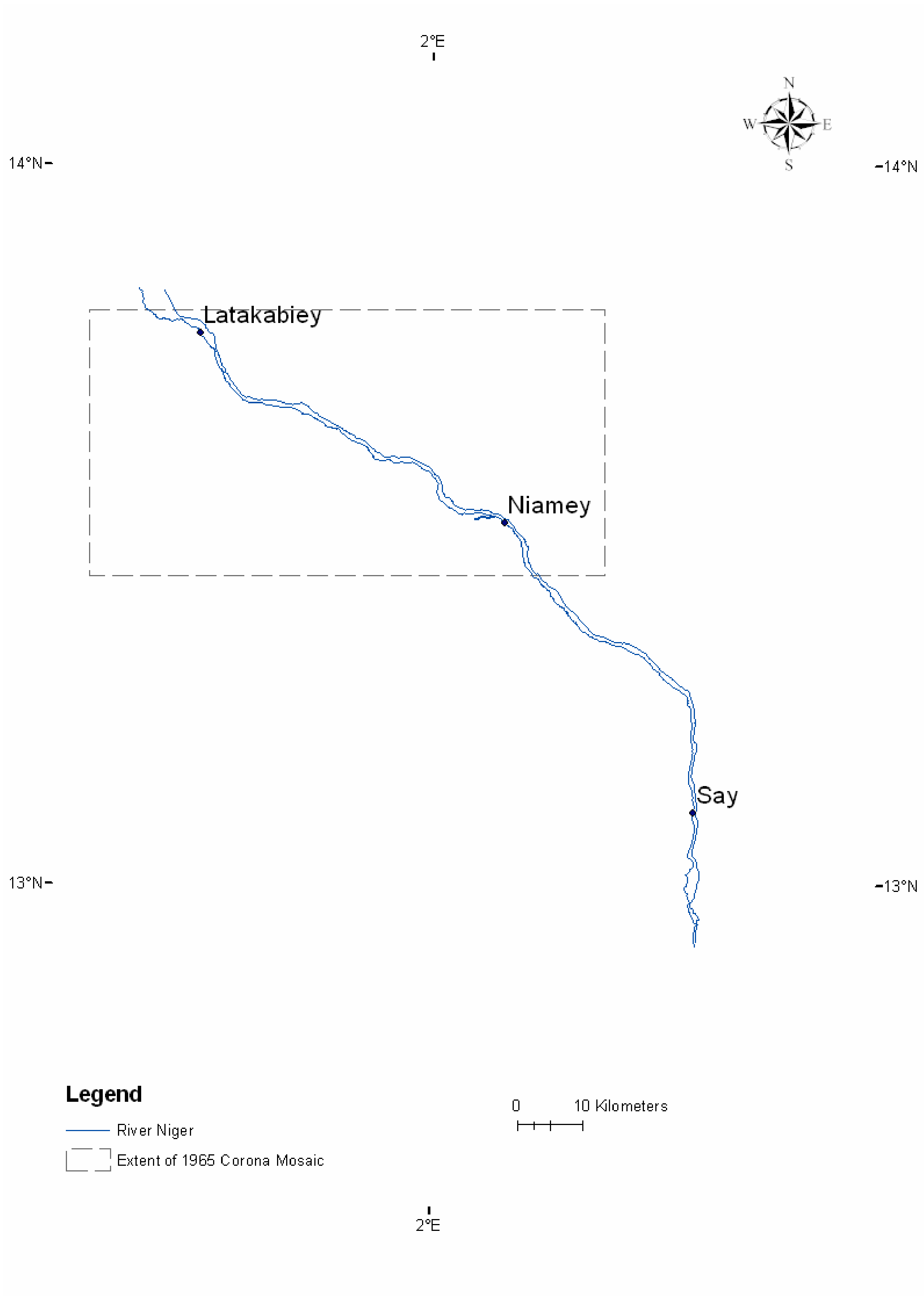

Figure II- 3: Reach 2 and the Corona 1965 extent

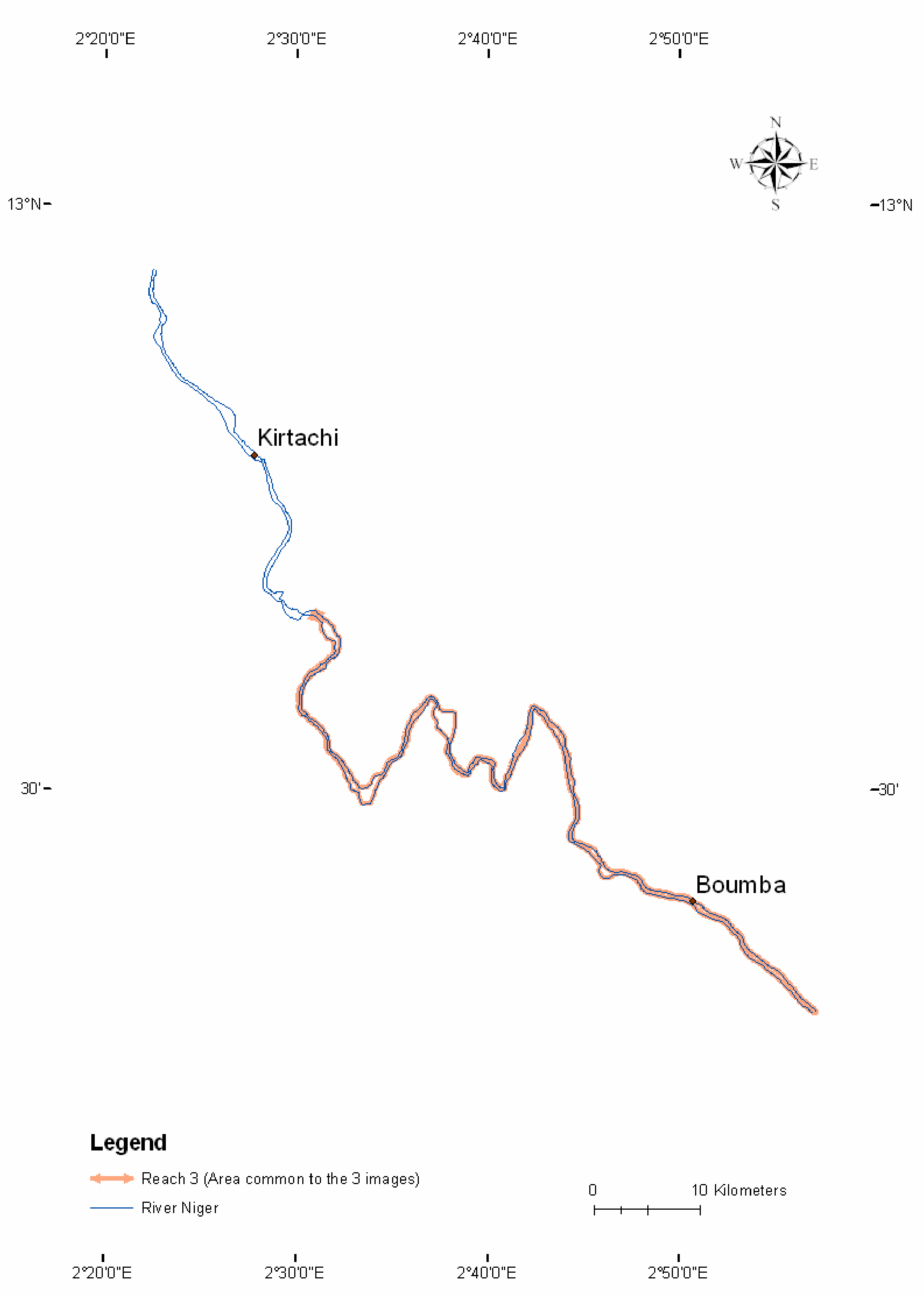

Figure II- 4: Reach 3

1.2. Methods

- **Data processing**

For each study reach, the older images were co-registered to the most recent image (the 1999 image) using features common to both features such as road intersections and infrastructure such as the Niamey airport. Between 6 and 10 points per image were used as tie points and the images were warped using a first order polynomial and nearest neighbour resampling. An example is found in part III of this work.

Image registration errors ranged from between 0.35 to 1.76 metres, which were acceptable considering the 1999 image pixel size of 30 metres.

- **Data analysis**

In order to study the planform change of the three reaches, it was necessary to characterise such channel form characteristics as the channel width, channel area as well as the vegetated island area. To achieve a more consistent discrimination of the water/land/vegetation boundary, the results of an unsupervised classification were used as the basis for deriving the riverbank lines. A comparison of a simple false colour combination (742) and the results of the unsupervised classification is presented in Figure II- 5 and Figure II- 6 to highlight the usefulness of this procedure for the delineation of the water-vegetation boundary. In Figure II- 6, water is represented in shades of blue; vegetation is represented in shades of green while bare soil is white and brown. The procedures for the unsupervised classification will be discussed in part III of this work.

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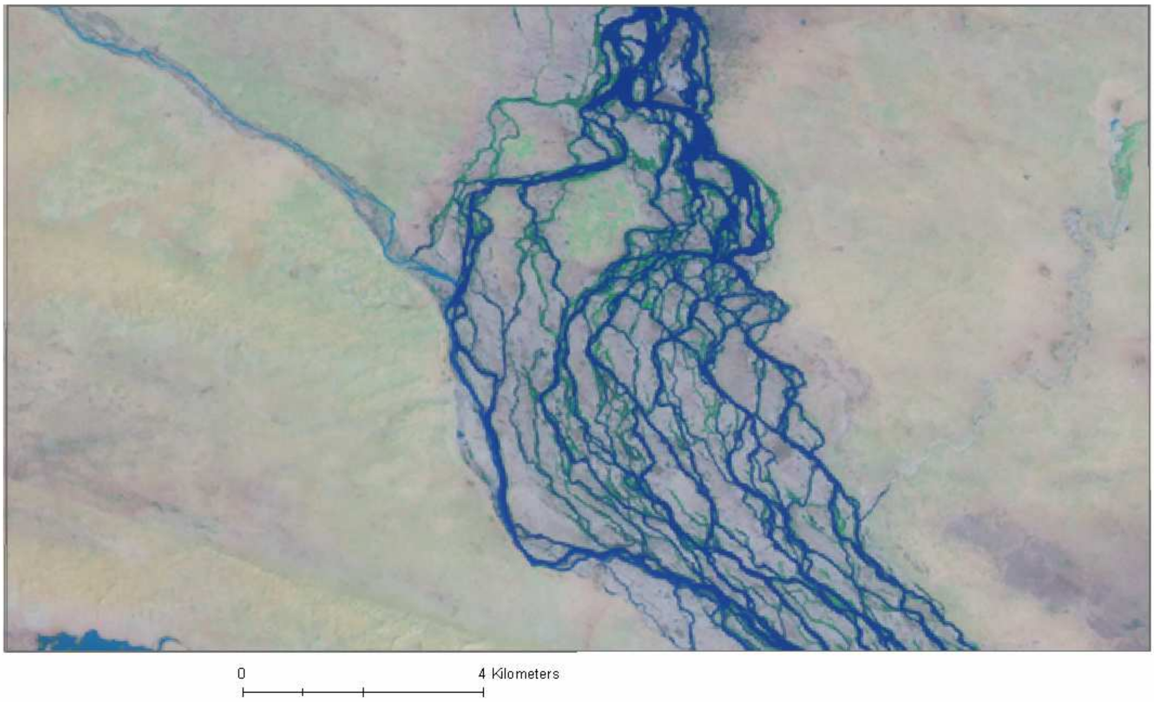


Figure II- 5: Example of a 742 false colour composite

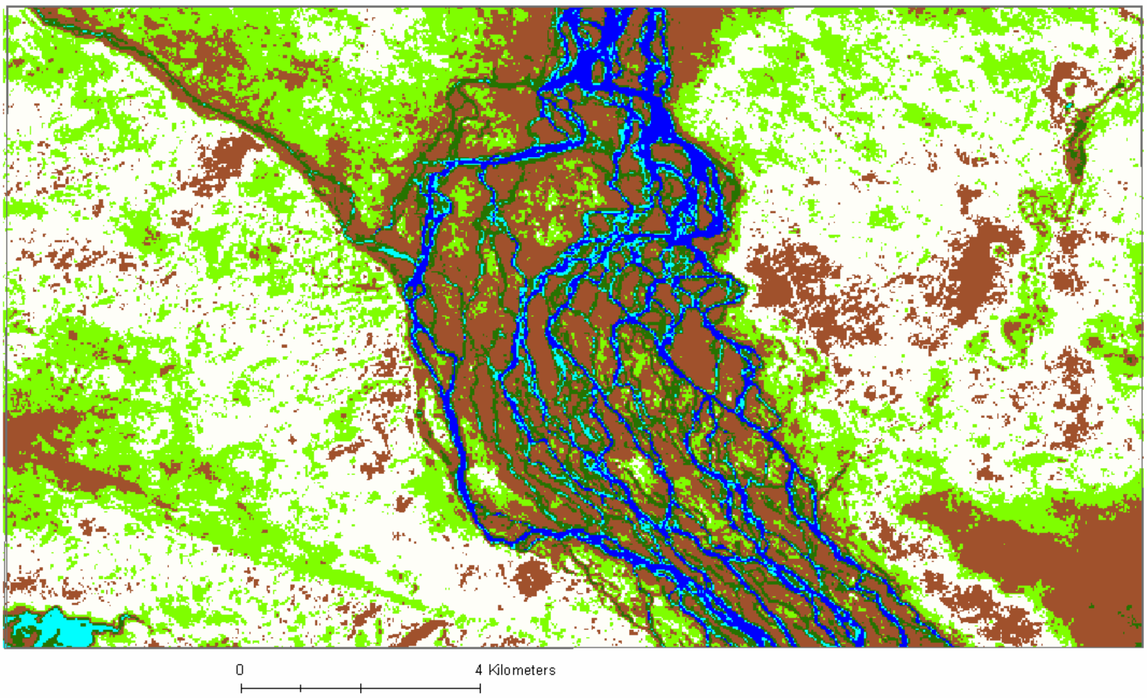


Figure II- 6: Example of the results of unsupervised classification

1.3. Channel variables

A geographic information system (GIS) was used to generate channel measurements necessary for the multi-temporal comparison of channel planform.

Richard et al. [2005] defined the active channel as the non-vegetated portion of the channel excluding middle channel bars and islands and the total channel as including middle channel bars and islands. For the purposes of this study, flooded vegetation was not considered as part of the active channel.

The **total river channel area** was derived by calculating the area of the polygon encompassing the limits of both banks of the river including the islands.

The active river channel area was derived by subtracting the island area from the total channel area.

River centre lines, which represent the river's mean position for a given period, were derived for each study reach as a line joining the channel mid-points calculated at a maximum of 500-metre intervals.

The **average channel width** was estimated as the ratio of the channel area to the length of the centreline.

A summary of the results of this analysis is presented in paragraph 1.4 . The results are presented graphically in appendix B for the three reaches.

1.4. Results and discussion

Alluvial rivers sometimes meander and migrate as they erode and deposit sediment along their banks. River migration rates are of interest to river managers because of the threat posed by highly mobile rivers to engineering structures as well as to human settlements.

In temperate regions, river migration rates are reported to range from 0.1 m/yr to more than 7.2 m/yr [*A Alvarez*, 2005]. An example of a more rapidly migrating river is the Brahmaputra-Jamuna River in southern Asia with a migration rate of up to 50 m/yr between 1830 and 1992 [*N I Khan and A Islam*, 2003]. In South America, Mertes et al [1996] reported a migration rate of 140 m/yr (or 3% of its channel width) for the Amazon River in Brazil, and citing Kalliola et al. , Mertes et al [1996] reported migration rates of up to 400 m/yr (or 37% of its channel width) for the Amazon River in Peru. In tropical Africa, Gilvear et al. [2000] reported a migration rate of up to 33 m/yr for the Luangwa River in Zambia.

In terms of river migration, the middle Niger River does not exhibit an excessive migration and its centreline has remained relatively stable between the 1970s and 1999 although the three study reaches have widened or contracted in the same period. The derived polygons delineating the riverbank lines, islands, as well as the derived river centrelines are presented in appendix B, and a summary of the results are presented in the following section.

For all three reaches, the results show the river's response to river discharge and sediment supply by the adjustment of its plan form such as the excision of ridges from the floodplain, bank erosion, and development of anabranches as well as the abandonment of anabranches.

1.4.1. River centreline evolution

The movement of the derived centrelines for a given period was determined with respect to another period for the same reach. The mean channel migration was determined in ArcGIS and is presented in appendix B (Figure B- 12 to Figure B- 20 for reach 1, Figure B- 44 to Figure B- 52 for reach 2, and Figure B- 78 to Figure B- 79 for reach 3) . The mean migration distances and rates for each reach are summarized in Table II- 2. The migration rate as a function of the river's mean width is also presented in the migration column.

Table II- 2 : Migration rates for the three study reaches

Reach	Period	Δt (years)	Mean width over the period (m)	Mean centreline movement (m)	Migration	
					Rate (m/yr)	Rate per width (m/w/yr)
1	1979-1984	5	1530	197.2	41.7	0.027
	1984-1992	8	1620	119.1	14.9	0.009
	1992-1999	7	1570	84.4	12.1	0.007
2	1975-1984	9	710	103.2	11.5	0.016
	1984-1989	5	735	51.5	10.3	0.014
	1989-1999	10	740	48.7	4.9	0.007
3	1973-1984	11	420	71.1	6.5	0.015
	1984-1999	15	420	27.9	1.9	0.005

For all three reaches, the period between the 1970s and 1984 witnessed the largest centreline movement. The time-averaged migration rates for the three reaches are calculated and presented in Table II- 3.

Table II- 3 : Time-averaged migration rates for the three study reaches

Reach	Migration rate (m/yr)	Migration rate per width(m/w/yr)
1	20.6	0.013
2	8.5	0.012
3	3.8	0.009
Overall	10.9	0.011

The overall centreline migration rate of the three reaches is 10.9 m/year and 0.011 m/width/year.

When the Niger River's width and the fluctuation in river discharge are taken into account, the observed centreline migration rates are not elevated for the middle Niger River. The other observed changes in channel form are presented in paragraph 1.4.2 and are discussed in paragraph 1.4.3.

1.4.2. Change in channel form

1.4.2.1. Reach 1

An analysis of the images indicated that for reach 1 (see Figure II- 7), the following observations were made for the period between 1979 and 1999.

- 1979-1984: A significant increase in channel area along with island area was observed between 1979 and 1984.
- 1984-1992: Channel area decreased between 1984 and 1992, but island area increased during the same period.
- 1992 – 1999: The total channel area remained near the 1992 level but island area increased slightly, causing a reduction in the active channel area.

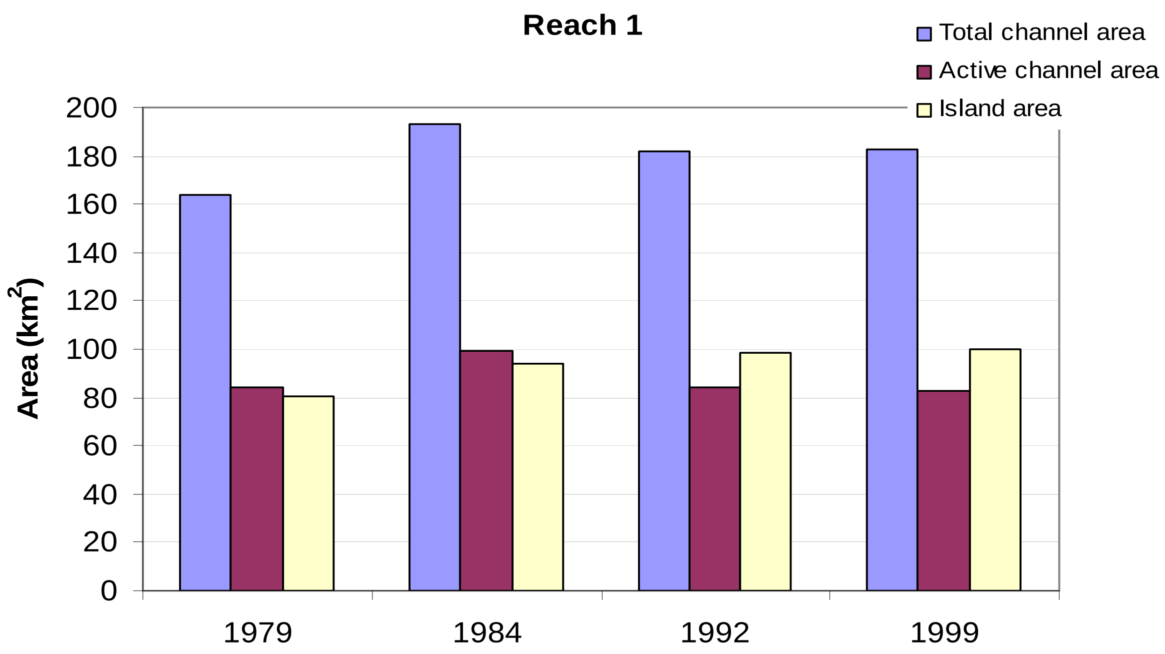


Figure II- 7: Channel area change in reach 1

Between 1979 and 1999, the middle Niger's channel in reach 1 expanded (1979-1984) and contracted (1984 -1999) in response to a variety of changes (see Figure II- 8).

The most significant change in average channel width occurred around 1984, with a significant expansion in channel width between 1979 and 1984 while a continuous reduction of average channel width was observed from 1984 up to 1999.

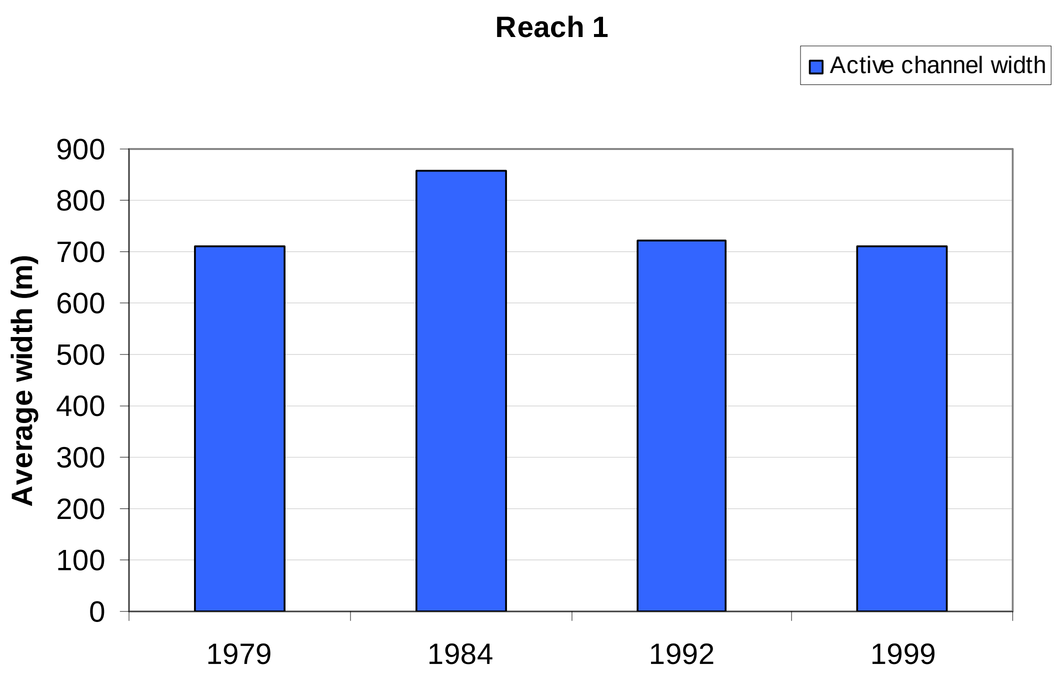


Figure II- 8: Channel width change in a portion of reach 1

1.4.2.2. Reach 2

The change in channel area in reach 2 is summarized in Figure II- 9.

- 1975-1984: As in reach 1, between 1975 and 1984 total channel area increased significantly. The measured islands area also increased between 1975 and 1984 but the active channel area also increased.
- 1984-1989: Channel area reduced in reach 2 between 1984 and 1989. Island area continued to increase causing a reduction in the active channel area.
- 1989-1999: Channel area had increased to 1984 levels by 1999. The channel area increased with a slight decrease in total island area.

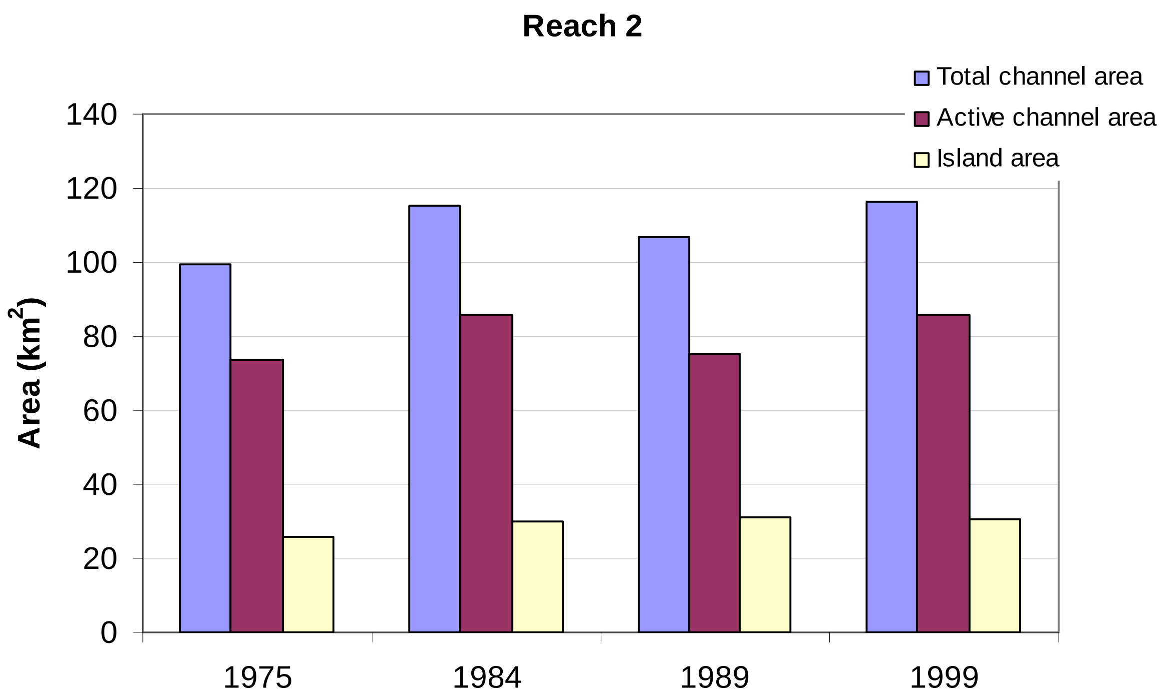


Figure II- 9: Channel area change in reach 2

Between 1975 and 1999 the active channel width of reach 2, contracted then expanded. As in reach 1, the most significant changes in average channel width occurred around 1984. Channel width increased between 1975 and 1984, while channel contraction occurred between 1984 and 1989. The channel width of reach 2 widened and attained the 1984 level (see Figure II- 10).

- 1975-1984: The active channel width increased significantly between 1975 and 1984.
- 1984-1989 : The active channel width narrowed between 1984 and 1989
- 1989-1999: Between 1989 and 1999, the channel area and channel width increased with a slight decrease in total island area.

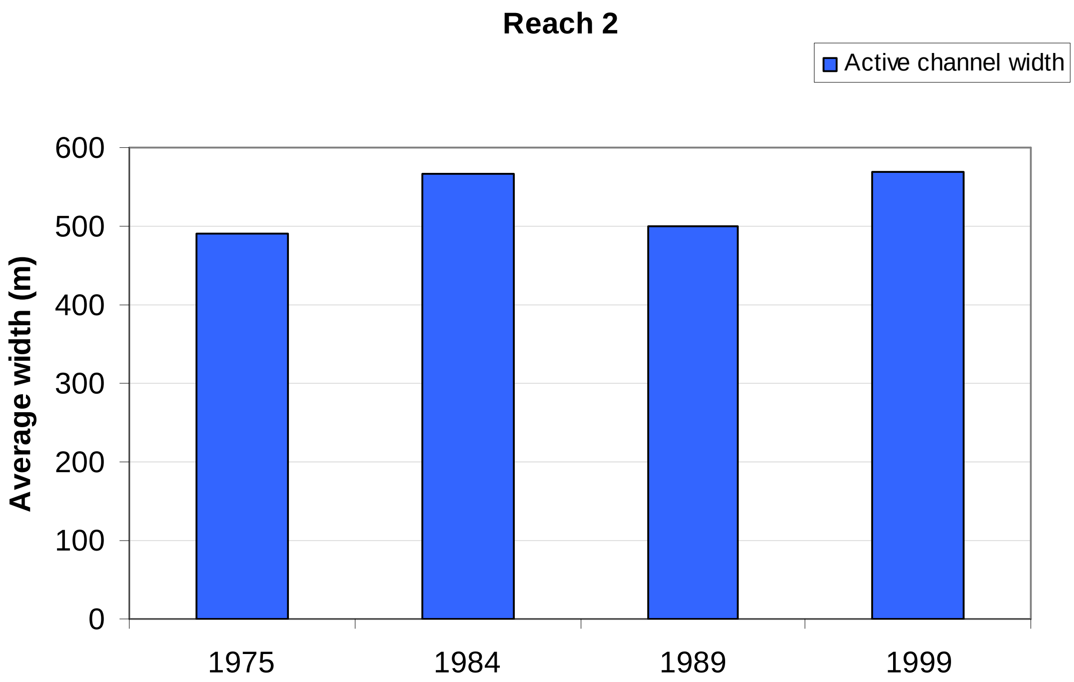


Figure II- 10 : Channel width change in reach 2

A comparison of the channel plan form between 1965 and 1999 was also made for a ~ 70 km stretch of reach 2 using a Corona image mosaic for October 1965 (see Figure II- 11 and Figure II- 12). The 1975 and 1999 states are compared with the 1965 imagery.

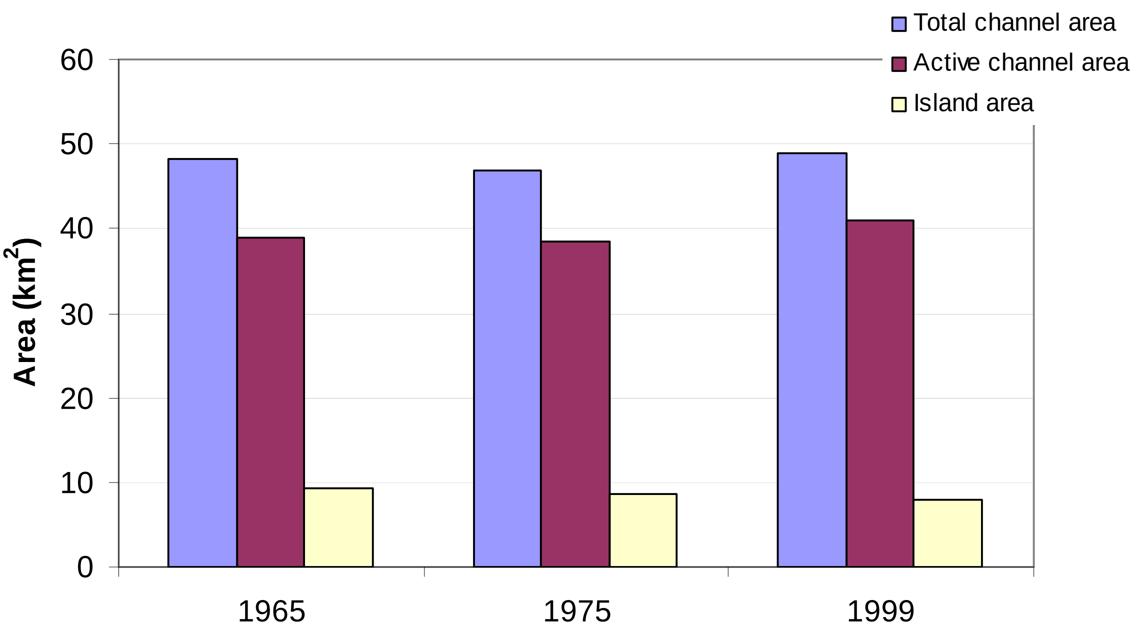


Figure II- 11: Channel area change in a portion of reach 2

The results infer that reach 2 was already in a narrowing phase by 1975 as it narrowed slightly between 1965 and 1975 over a smaller area.

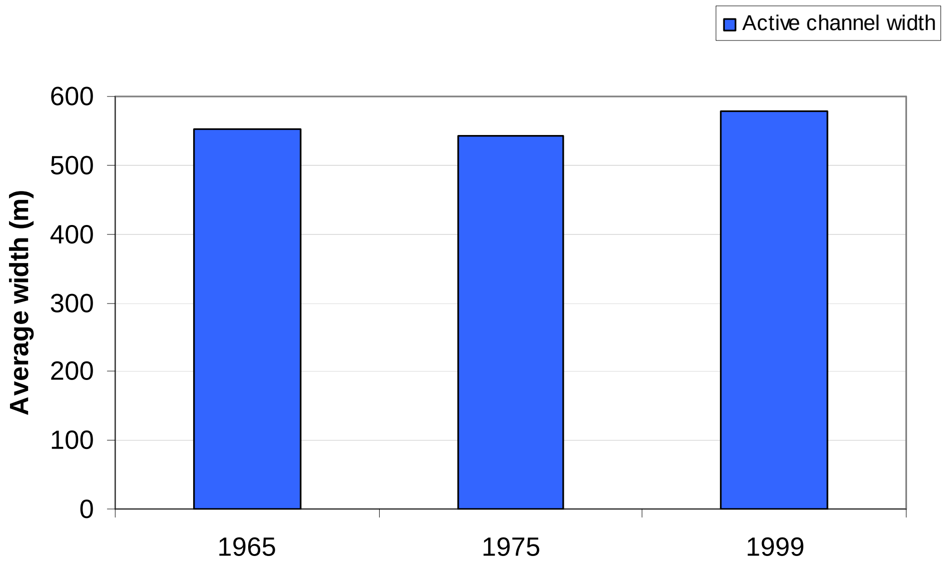


Figure II- 12: Channel width change in a portion of reach 2

1.4.2.3. Reach 3

In comparison to reach 1 and reach 2, reach 3 was relatively unchanged between 1973 and 1999 (see Figure II- 13 and Figure II- 14).

- 1973 – 1984: Total island area increased slightly in reach 3 between 1973 and 1984, causing a slight decrease in channel area in the same period.
- 1984 – 1999: Total island area increased more significantly than the period between 1973 and 1984, causing a decrease in the active channel area even though the total channel area increased slightly.

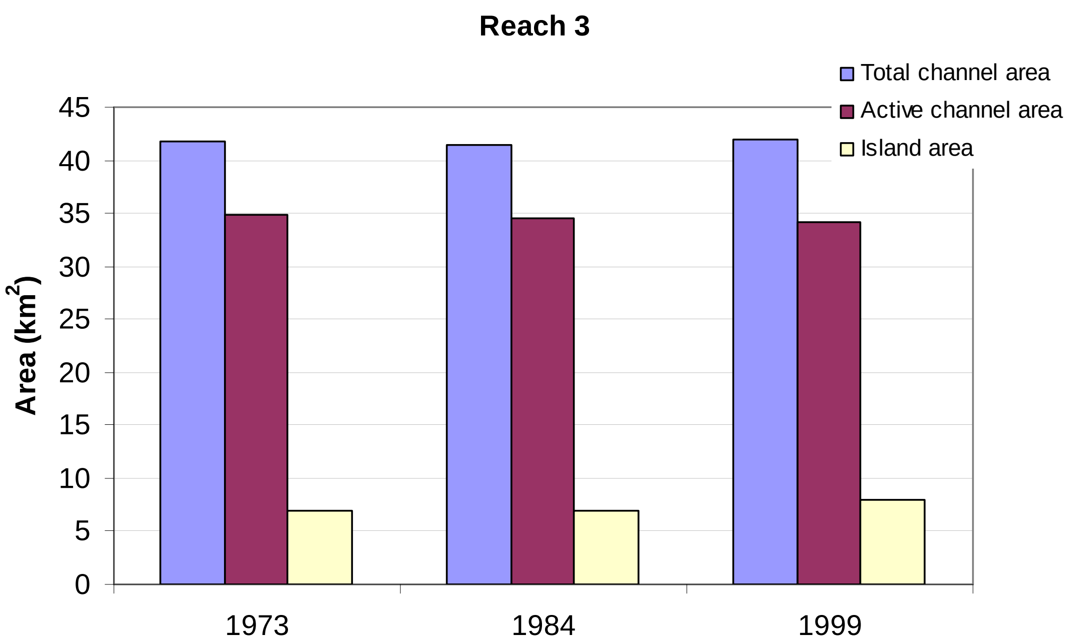


Figure II- 13: Channel area change in reach 3

Contrary to the observations in reaches 1 and 2, between 1973 and 1984, reach 3 narrowed slightly and this trend continued between 1984 and 1999 (see Figure II- 14). It is noteworthy that a large stretch of this reach of the middle Niger River is confined by the nature of its banks and therefore lateral channel movement is limited.

- 1973 – 1984: The reduction in total average width was because of an increase in total island area increased slightly in reach 3 between 1973 and 1984.
- 1984 – 1999: Due to the continuous increase in island area, the active channel width of reach 3 decreased further between 1984 and 1999.

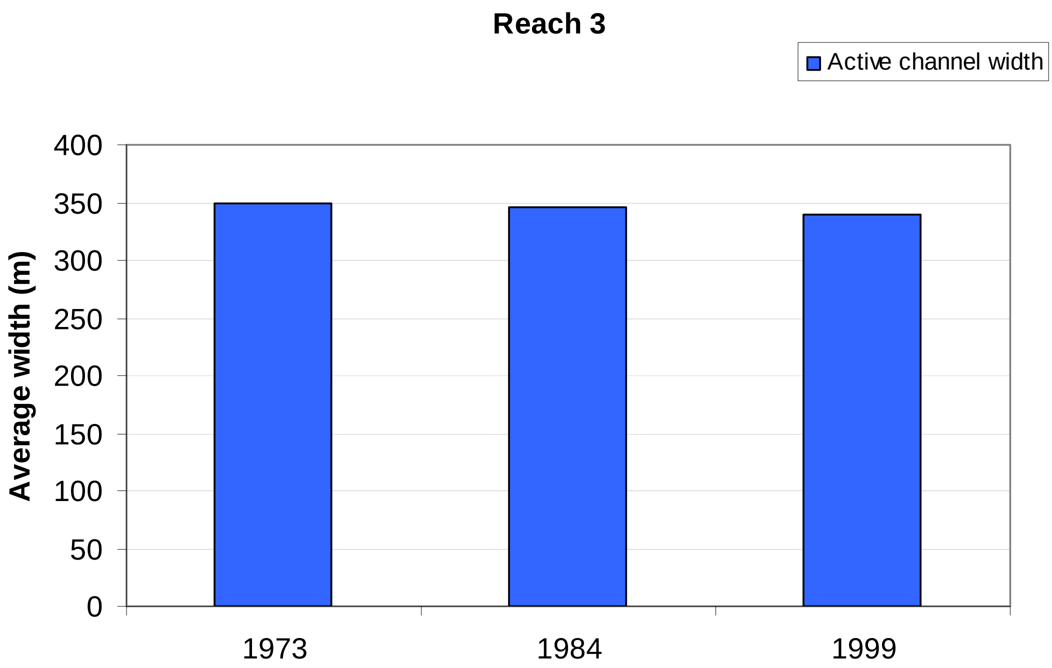


Figure II- 14: Channel width change in reach 3

1.4.2.4. Summary

The channel characteristics of the three study reaches are summarized in Table II- 4 (channel area) and Table II- 5 (channel width).

Table II- 4: Channel area characteristics of three reaches of the middle Niger River.

Reach	**Year**	**Total channel area (km²)**	**Total island area (km²)**	**Active channel area (km²)**	**Island/channel ratio**
1	1979	164.17	80.20	83.97	0.489
	1984	193.10	93.90	99.20	0.486
	1992	182.31	98.29	84.02	0.540
	1999	182.73	99.92	82.81	0.547
2	1975	99.69	25.87	73.82	0.259
	1984	115.41	29.82	85.60	0.258
	1989	106.59	31.30	75.29	0.294
	1999	116.30	30.49	85.81	0.262
3	1973	41.71	6.85	34.85	0.164
	1984	41.47	6.87	34.59	0.166
	1999	41.97	7.87	34.10	0.187

- In reach 1, total channel area increased sharply between 1979 and 1984, reduced between 1984 and 1992, and remained relatively stable between 1992 and 1999. The island area to channel area ratio has steadily increased since 1979 due mainly to anabranching in reach 1.
- In reach 2, two phases of total channel area increase were observed. The first phase of channel area increase occurred between 1975 and 1984, and a subsequent phase of channel area increase occurred between 1989 and 1999. Island area increased in reach 2 from 1975 up to 1989, and then slightly decreased between 1989 and 1999.
- Relative to reaches 1 and 2, reach 3 has changed only slightly. A slight decrease in the total channel area was observed between 1973 and 1984, while between 1984 and 1999 the total channel area slightly increased. The active channel area in reach 3 has steadily decreased since 1973 due to the increase in island area.

The effects of the changing channel characteristics are reflected on the river's average width, which are compared in Table II- 5 for the three reaches.

Table II- 5 : Change in the average width of the middle Niger River

Reach	Year	Average Total channel width (km)	Average active channel width (km)
1	1979	1.39	0.71
	1984	1.67	0.86
	1992	1.57	0.72
	1999	1.57	0.71
2	1975	0.66	0.49
	1984	0.76	0.57
	1989	0.71	0.50
	1999	0.77	0.57
3	1973	0.42	0.35
	1984	0.42	0.35
	1999	0.42	0.34

- The width of the active channel in reach 1 increased between 1979 and 1984, and decreased between 1984 and 1992. The average active channel width measured for 1999 was the same as that for 1979.
- As with the channel area changes, the channel width measurements for reach 2 fluctuated between 1975 and 1999, increasing between 1975 and 1984, decreasing between 1984 and 1989 and increasing again between 1989 and 1999.
- The slight fluctuations in the total channel area of reach 3 did not affect the total channel width to the nearest 100 metres; however, the active channel width decreased slightly between 1984 and 1999.

1.4.3. Factors responsible for channel form change

River channels are known to adjust to a variety of factors and the identification of the principal causes of river channel adjustment can be complex. One of the common causes of river channel adjustment is climatic perturbations such as fluctuations in the volume of annual precipitation and flood frequency about a steady long-term average. In this case, river channels may be expected to widen flowing a period of relatively high flows and to contract during below average flow periods.

Channel widening can occur due to bank erosion without incision of the riverbed, but it can also occur due to the instability of steep banks following riverbed incision.

Channel narrowing has been reported to take place due to the encroachment of vegetation. Channel narrowing in sinuous channels can occur when the rate of alternate point bar exceeds the retreat rate of the opposite cut bank. In anabranching systems, narrowing occurs when marginal anabranches are abandoned either as a result of decreasing discharge or as a result of sediment deposition [*The ASCE Task Committee on Hydraulics Bank Mechanics and Modeling of River Width Adjustment*, 1998].

1.4.3.1. Middle Niger River channel response to river discharge

Montgomery and Buffington [1997] as well as Lane [2004] noted that many channels are insensitive to all but catastrophic peak discharges. The ASCE Task Committee on Hydraulics Bank Mechanics and Modeling of River Width Adjustment [1998], citing Wolman noted that significant bank erosion occurred during relatively small but frequent flow events. On the other hand, it has been reported that significant bank erosion was caused by large flood events with recurrence intervals of decades or centuries [*A Gupta and H Fox*, 1974].

For this study, the cumulative annual discharge was applied as a useful simplification for qualitatively evaluating the effect of river discharge on channel size, as it integrates the effects of a range of flows over the long-term.

The cumulative volume of water discharged by the Niger River at Niamey could be considered as representative of the middle Niger's discharge for the three reaches under consideration. It was also necessary to use data from the Niamey station in the evaluation of channel response to river discharge because it has the most complete data set for the middle Niger River. The cumulative discharge volume series between 1960 and 2000 (covering the period of available satellite image data) is presented in Figure II- 15 with a 5-year mobile average to demonstrate the series trend.

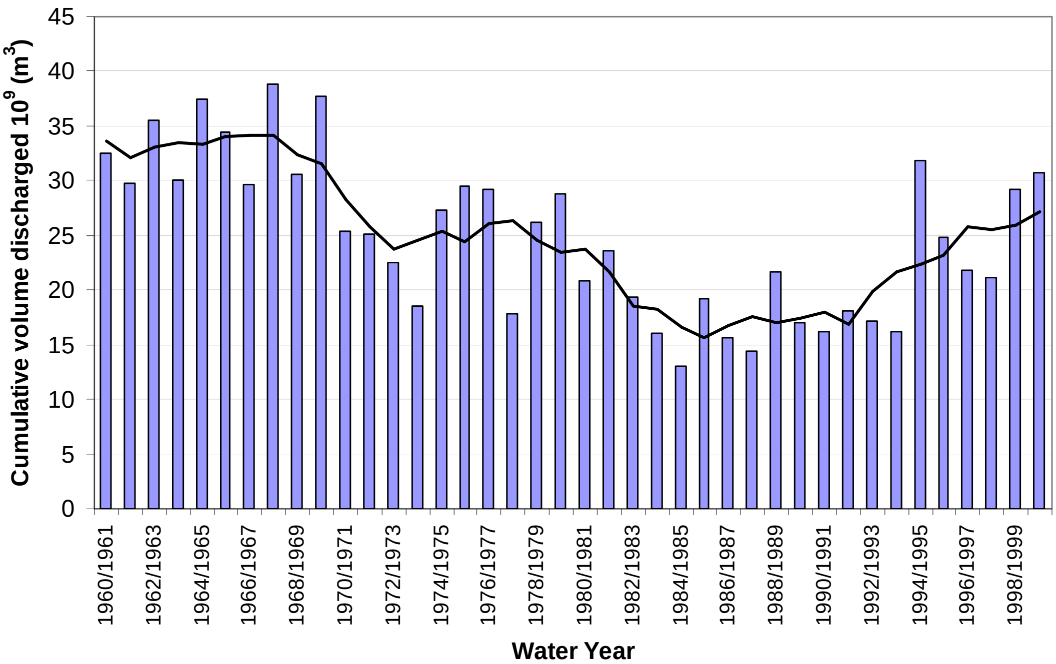


Figure II- 15: Cumulative volume discharge of the Niger River at Niamey (1960-1999)

The approximate annual cumulative discharge volume for the four periods to be compared for the three reaches are 1973-1979 (~25 billion m^3), 1984 (~16 billion m^3), 1989-1992 (~18 billion m^3) and 1999 (~27 billion m^3).

In addition to the cumulative discharge volume series, the characteristics of flood discharges over a threshold of 1700 m^3/s (corresponding to a flood with a 2-year return period) are presented in Table II- 6.

Table II- 6 : Magnitude of floods on the middle Niger River at Niamey (1960-2000)

Date of flow	Duration above the threshold (days)	Peak discharge	Recurrence interval of peak discharge (years)
1960/61	75	1870	2-5
1961/62	40	1760	2-5
1962/63	86	2060	5-10
1963/64	63	1850	2-5
1964/65	100	2080	5-10
1965/66	91	1950	5-10
1966/67	81	1970	5-10
1967/68	121	2340	30-40
1968/69	71	1920	2-5
1969/70	116	2360	30-40
1970/71	43	1820	2-5
1971/72	55	1820	2-5
1974/75	66	1980	5-10
1975/76	79	2030	5-10
1976/77	60	1930	5-10
1978/79	34	1930	5-10
1980/81	84	1820	2-5
1981/82	23	1730	2-5
1988/89	17	1870	2-5
1994/95	32	1750	2-5
1995/96	1	1700	2-5
1998/99	11	1990	5-10
1999/2000	64	1830	2-5

Recurrence interval values were derived from discharge analyses (see Figure B- 93 and Table B- 4in the appendices)

Reach 1

- 1979-1984: Although the river discharge in 1984 was much lower than in 1979, the relatively high magnitude cumulative discharges experienced between 1974/75 and 1978/79 (see also Table II- 1 and Table II- 6) may have caused bank erosion and thus channel widening in the period between the 1979 and 1984 images. The time lag between bank erosion (~1979) and channel adjustment (after 1984) gives an indication of the time required for the Niger River to adjust to such flood induced perturbations.
- 1984-1992: Channel width decreased between 1984 and 1992 even though river discharge volume had increased slightly (see Figure II- 15). The period of below average river discharge caused the persistence of channel narrowing that was not reversed by the slight increase in river discharge between 1984 and 1992.
- 1992-1999: The total channel area increased mainly due to anabranching as the total island area also increased resulting in a reduction in the active channel area and width in spite of increasing discharge.
- Other observations: Cumulative island area has increased since 1979 due to the stabilization of mobile bars. The increase in the total island area between 1979 and 1999 is largely due to the enlargement of the anabranching portion of the middle Niger River between Ayorou and Kandadji by the excision of the existing flood plain and to some extent, to in-channel accretion

Reach 2

- 1975-1984: Reach 2 was wider in 1984 compared to 1975 despite the discharge at Niamey for the 1984 image being only 1050 m^3/s compared to 1650 m^3/s in the 1975 image. The active channel width increased very significantly between 1975 and 1984 due mainly to bank erosion that occurred between 1975 and 1984. The channel enlargement observed in the 1984 image can be explained by the period of relatively high river discharge between 1975 and 1984 (see Table II- 6). The influence of anabranching on the increase in channel width of reach 2 between 1975 and 1984 was minimal.
- 1984-1989 : The reduction in channel area and width between 1984 and 1989 was as a result of the long-term effects of the below average cumulative discharge on the Niger river even though the mean daily discharge on the image dates was higher in 1989 than in 1984. Compared to floods that occurred in the pre-1984 period the duration of the floods that occurred between 1984 and 1989 were shorter. A secondary reason for the

reduction in mean channel with for this period was the cut-off of some anabranches by sediment coming from intermittent streams.

- 1989-1999: With increasing river discharge, (in 1998 there was a 5-10 year flood see Table II- 6), the channel area and channel width increased with a slight decrease in total island area highlighting again the time lag between external factors and channel response.
- Other observations: Anabranching in reach 2 was the major cause of the increase in area of vegetated islands and ridges between 1975 and 1984.

Reach 3

- The reduction in mean total width was because of the reduction in discharge between 1973 and 1984. Reach 3 unlike reach 1 and reach 2 may not have undergone the channel widening that occurred before 1984 due to the strength of the Niger's banks in reach 3.
- The mean total channel width increased between 1984 and 1999 to pre-1984 levels in response to the significant floods of 1988, 1994 and 1998. Although the total channel width increased between 1984 and 1999, the active channel width decreased slightly due to an increase in island area.
- Other observations: Reach 3 has contracted slightly since 1973 in terms of active channel area at the same time as increasing discharge, river bed incision may therefore be occurring.

Discussion

Changes in flow regime and sediment supply have also been reported to result in river channel adjustment. The flow regime change of the middle Niger River is discussed in Part IV of this work.

Reach 1, and to a lesser extent reach 2 are anabranching stretches that according to Huang and Nanson [2007] possess individual channels that are clearly separated at bankfull discharge by sub-aerial vegetated islands and ridges in contrast to braided rivers in which multiple channels are separated by sub-aqueous bars as part of a mobile bed within a bankfull cross-section.

Applying a bed load formula and basic river flow and geometry relationships, Huang and Nanson [2007] related bed sediment discharge and to river width to depth ratio. They reached the conclusion that channel width reduction leads to increased sediment transporting capacity up to an optimum width-depth ratio.

In summary, Huang and Nanson [2007] posited that anabranching occurs in order to reduce channel width and thus increase the section's sediment transporting capacity. Anabranching systems have one or two dominant channels and thus the forming of multiple channels does not reduce the improvement in sediment transporting capacity achieved by channel width reduction.

Some of the multiple channels formed by anabranching could serve as an efficient means for sediment sequestration for a rapidly aggrading floodplain.

It can be inferred that the anabranching occurring mainly in reach 1 and to a lesser extent in reach 2 are the channel's response to increased sediment supply.

1.4.3.2. Other possible reasons for channel adjustment

According to Hagerty [1991a; b], bank erosion leading to channel widening can also be unrelated to the magnitude and intensity of river discharge but to the rise in groundwater levels that generate erosion through sapping or piping processes. Leblanc et al. [2008] reported the incidence of rising groundwater levels in a 500 km² study area about 60 km from the Niger at Niamey, from 1963 and more rapidly from ~1982 due mainly to land clearance. Sapping and piping erosion processes have not been investigated for the study area but could be contributing to bank erosion considering the reported rising groundwater levels. Descroix et al. [2005] linked widening riverbeds to a reduction in vegetation cover and found that the length of response times were related to vegetation cover and anthropogenic influences.

2. Lateral sediment sources: Increasing alluvial deposits from "koris"

One of the most apparent changes noted from the multi-temporal satellite imagery in the study area was the enlargement of the alluvial deposits from small ephemeral streams that sustain runoff for only very short periods during the rainy season. These ephemeral streams, locally known as "koris" flow towards the Niger River. These "koris" are located on either side of the Niger River as described in Figure II- 16.

2.1. Data

A summary of the data used in characterizing the evolution of the alluvial deposits of these alluvial streams is presented in Table II- 7. The images compared are for the same period of the year for same season comparison. The centre regional **Agrhymet** provided the 1984 imagery while the other imagery was obtained from the **GLCF**.

Table II- 7 : Satellite data used to monitor the change in alluvial deposit area

Image date	Path/row	Pixel size(m)
22/11/1975	207/051	57
14/11/1984	193/051	28.5
20/11/1989	193/051	28.5
31/10/1999	193/051	28.5

2.2. Methods

An unsupervised classification algorithm was applied to locate these alluvial deposits in the satellite imagery and the areas were measured in ArcGIS.

2.3. Results

The observed changes between 1975 and 1999 in one of these "kori" deposits located approximately at the position of the dashed arrow in Figure II- 16 (near Kourtéré) are illustrated in Figure II- 17 to Figure II- 20, where islands are represented in dark brown and the channel extent in light blue .

It can be seen that the area covered by the deposits increases from 0.16 km² in 1975 to about 1.24 km² in 1999. Similarly changes had been noted by Chinen [1999] for the same gullies and deposits by analysing aerial photography between 1950 and 1975. Leblanc et al. [2008] analysed aerial photographs between 1950 and 1992 for a 2 km² catchment in Wankama about 60 km north-east of Niamey, reported that gullies continuously increased in number and length resulting in a doubling of the drainage density.

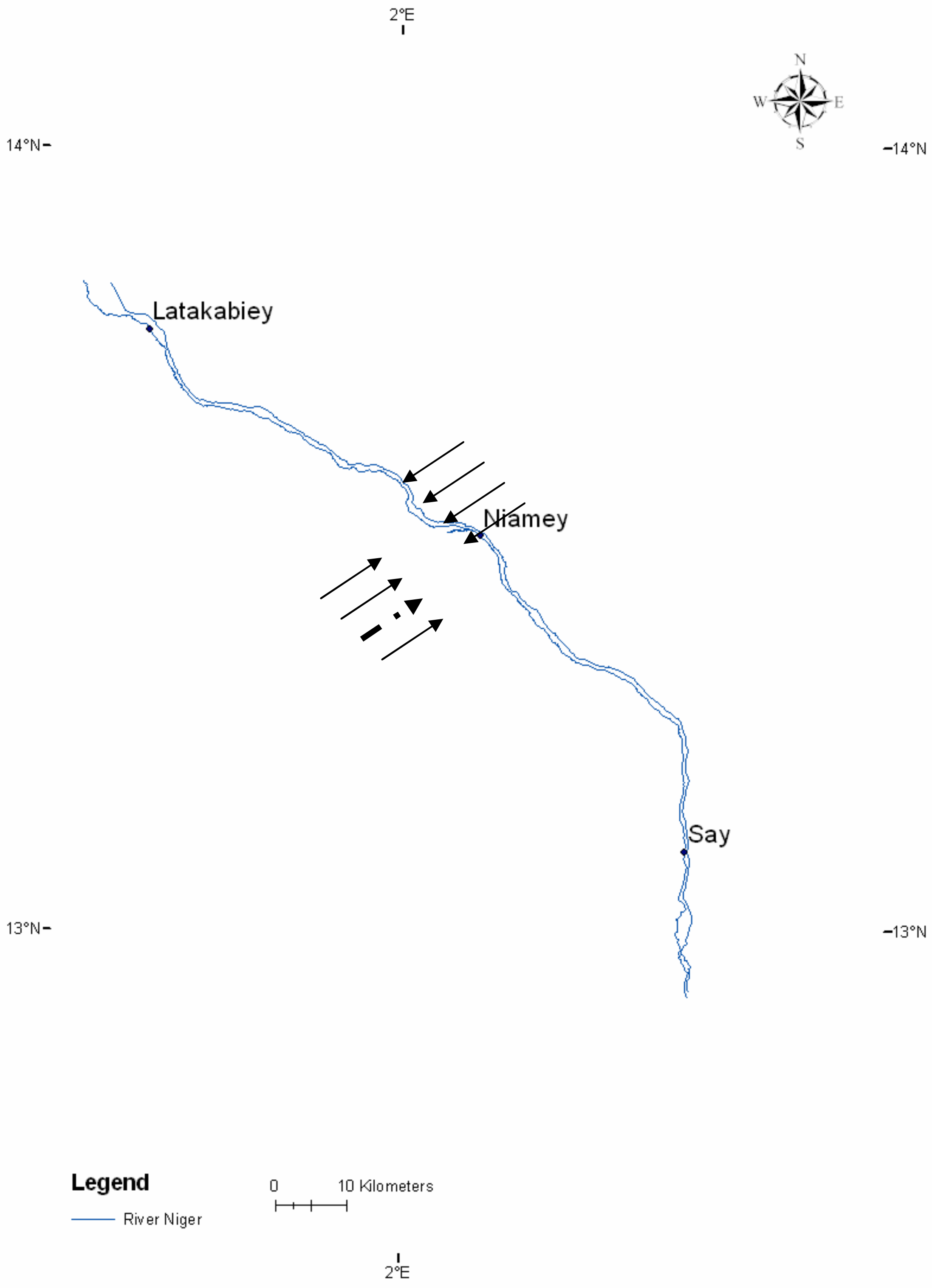


Figure II- 16: Lateral sediment sources of the middle Niger River

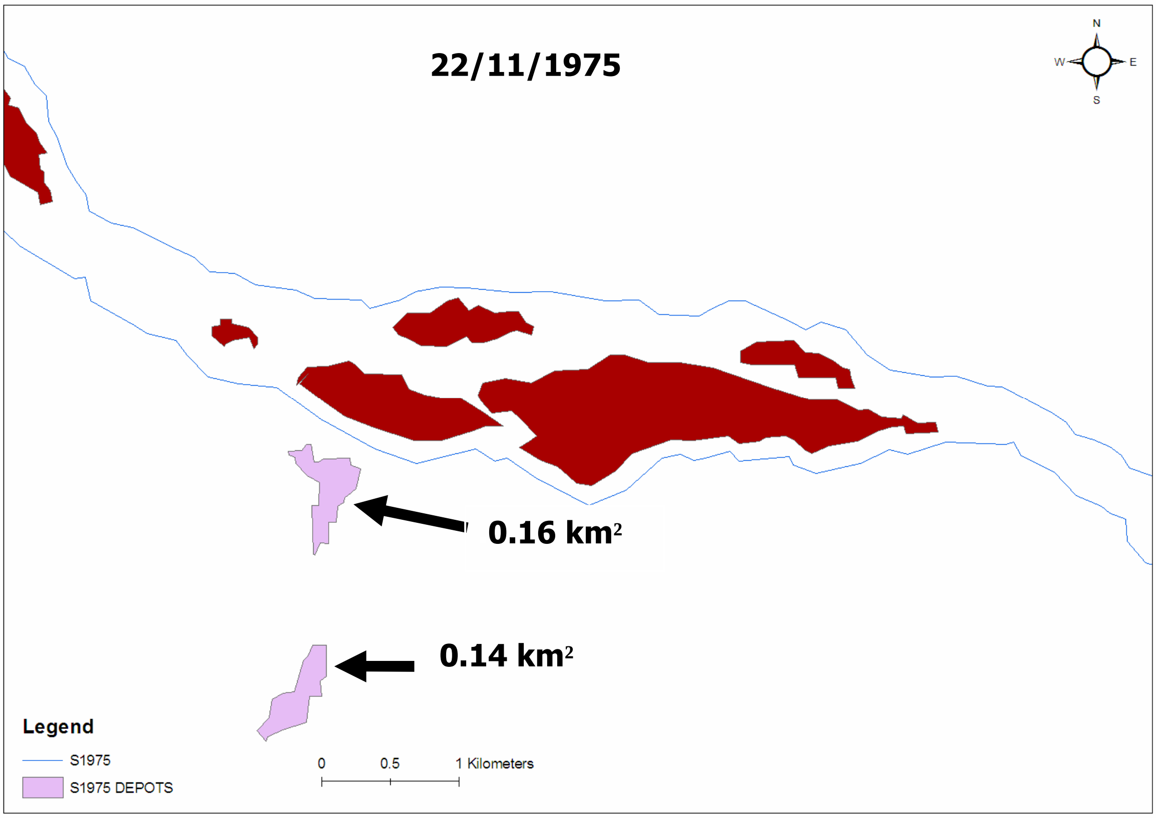


Figure II- 17: Alluvial deposits 1975

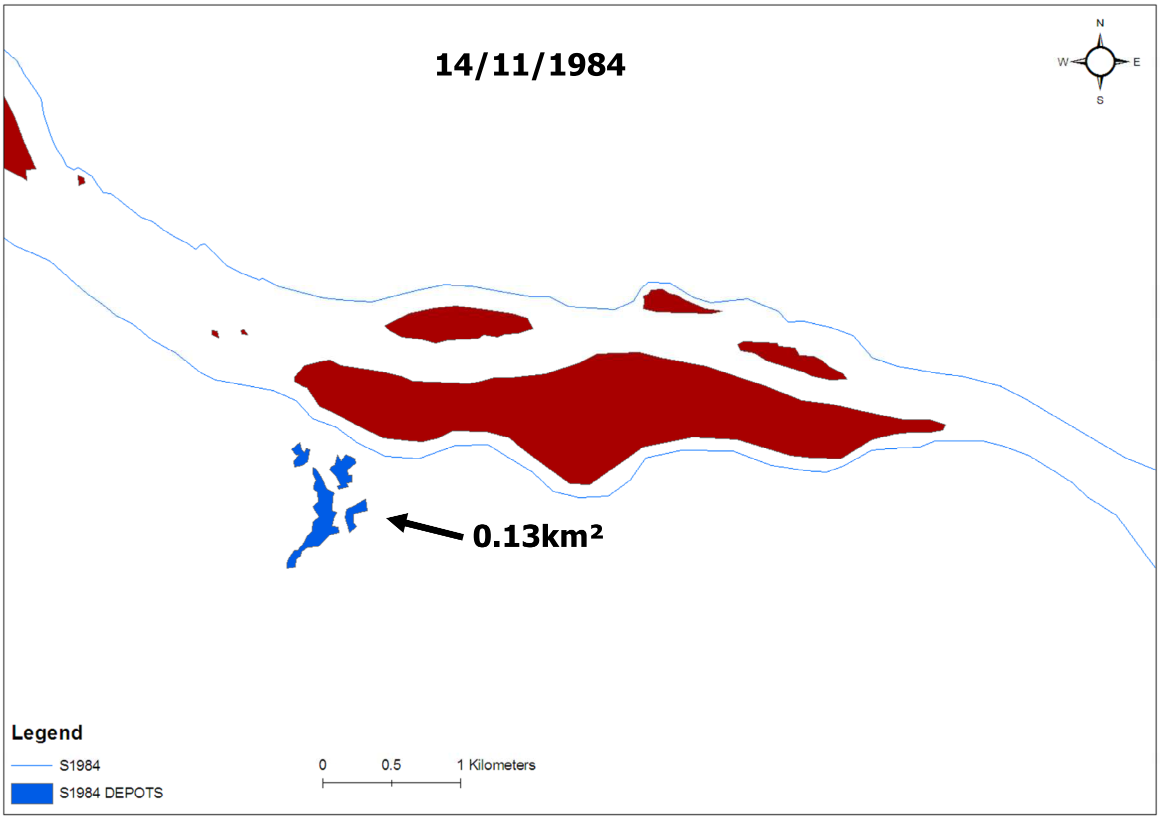


Figure II- 18: Alluvial deposits 1984

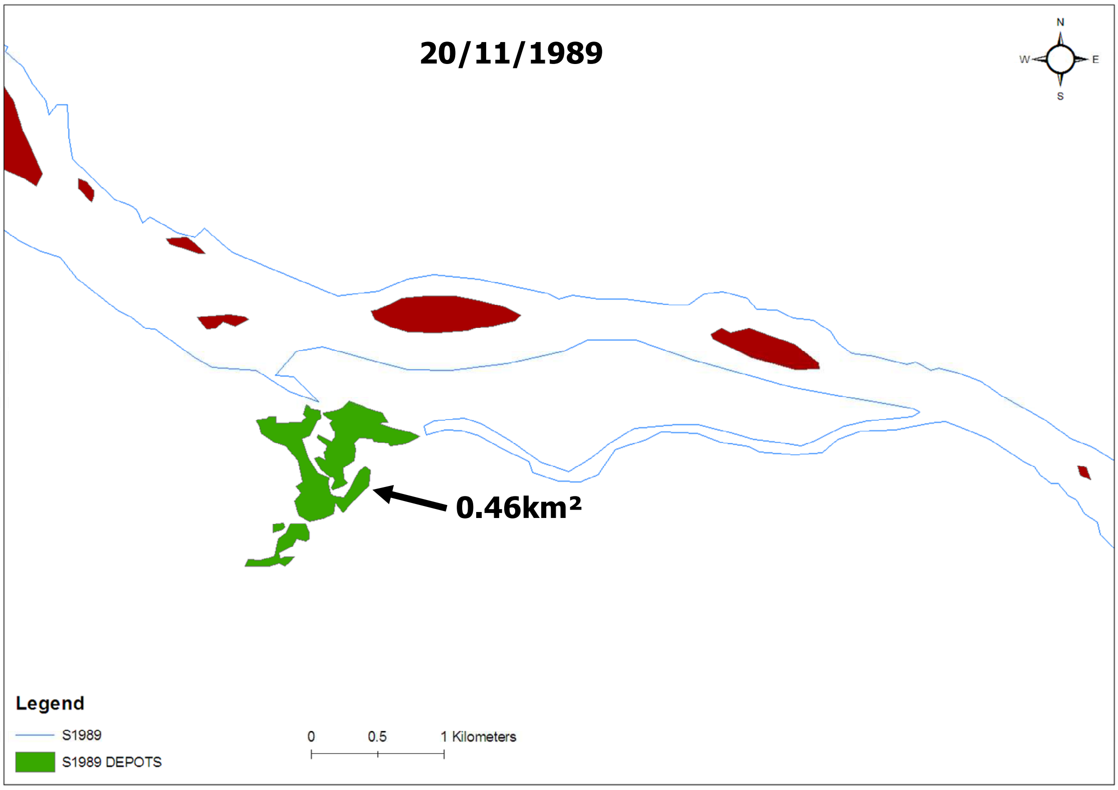


Figure II- 19: Alluvial deposits 1989

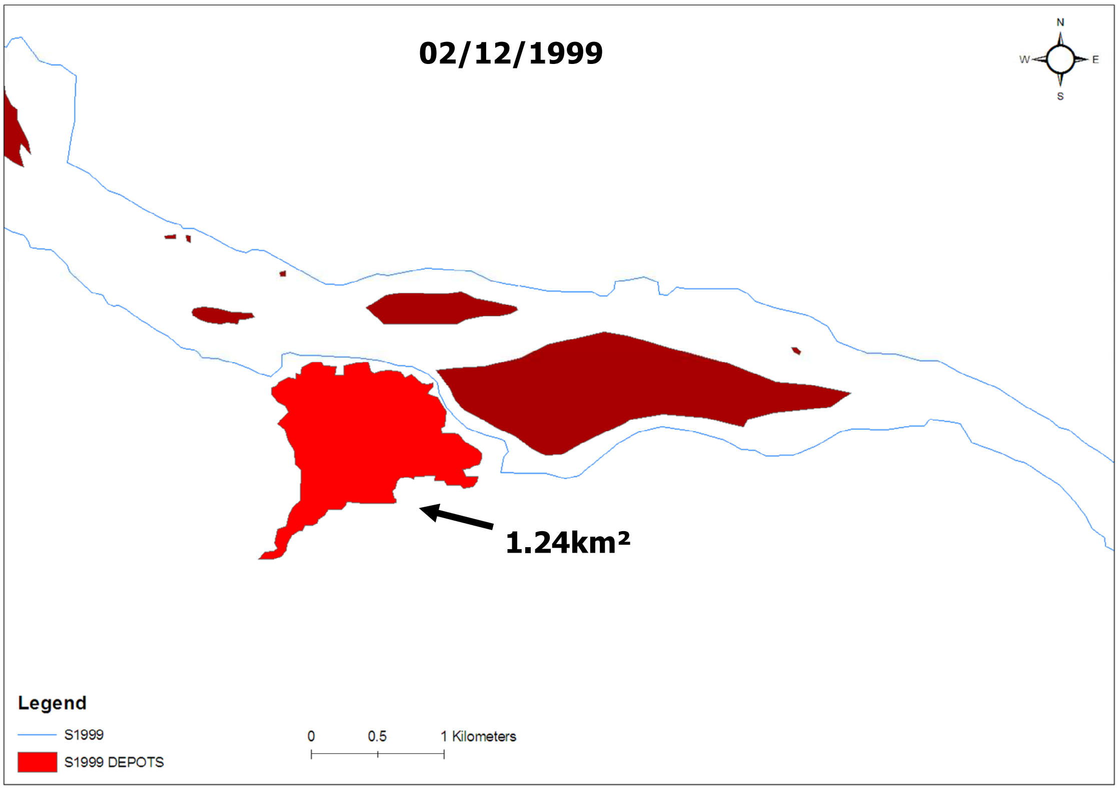


Figure II- 20: Alluvial deposits 1999

2.4. Summary

The trend of increasing alluvial deposits near the Niger River near Niamey is illustrated in Figure II- 17 to Figure II- 20. These ephemeral streams appear to have continued to increase in size and in length since the 1950s because of land clearance. The increasing amounts of sediment they deposit make them an important source of sediment to the Niger River. Further work might be necessary to quantify the discharges of these unmeasured ephemeral streams for a better understanding of the impact they have on the Niger River in terms of river discharge during the rainy season as well as in terms of sediment input. The study of these "koris" at the time of writing this thesis is the thesi work of I.Mamadou at the University of Paris.

3. Evolution of river bed level

River bed level change was evaluated for two portions of the middle Niger River using longitudinal profiles established by the “ Institut Géographique National” **IGN** in 1978 IGN [*IGN*, 1979] and data from field work carried out in August 2007. The availability of historic maps and field resources contrained the investigation to reaches 2 and 3. The same survey benchmarks as references in order to compare the two data. The mean change in bed level was calculated.

3.1. Data

Information regarding the 1978 data is presented in Table II- 8.

Table II- 8 : Riverbed level for the middle Niger River 1978

Map Name	Survey date	Edition date	Scale
Réalisation cartographique préliminaire à l’établissement du modèle mathématique du fleuve Niger (I.G.N. Paris)	1978	1979	1 :50 000

3.2. Methods

Riverbed levels were measured by lowering a 25 kg weight attached to a cable into the river from a boat and reading off the depth from the counter (accurate to the nearest centimetre) attached to the cable. The river depth measurements were made at between 5 and 10 verticals of cross-sections about 1 km apart.

The position of each depth measurement was noted from a hand held Global Positioning System (GPS). Approximately every 4 kilometres, the river water level was determined by surveying from the “Nivellement Géographique de l’Afrique de l’Ouest” (NGAO) benchmarks used in the IGN 1978 survey to the point of water level measurement. The riverbed level was calculated as the difference between the water level and the measured depth.

The lowest vertical of each cross-section for the 2007 survey as well as the 1978 survey were used to evaluate the change in riverbed profile between the two dates.

3.3. Results

The riverbed levels compared for a portion of reach 2 are presented in Figure II- 21 for reach 2 and the bed level change between the 1978 and 2007 is plotted in Figure II- 22.

The portion of reach 3 compared between 1978 and 2007 is shown in Figure II- 23 in relation to reach 3 while the observed bed level change is plotted in Figure II- 24.

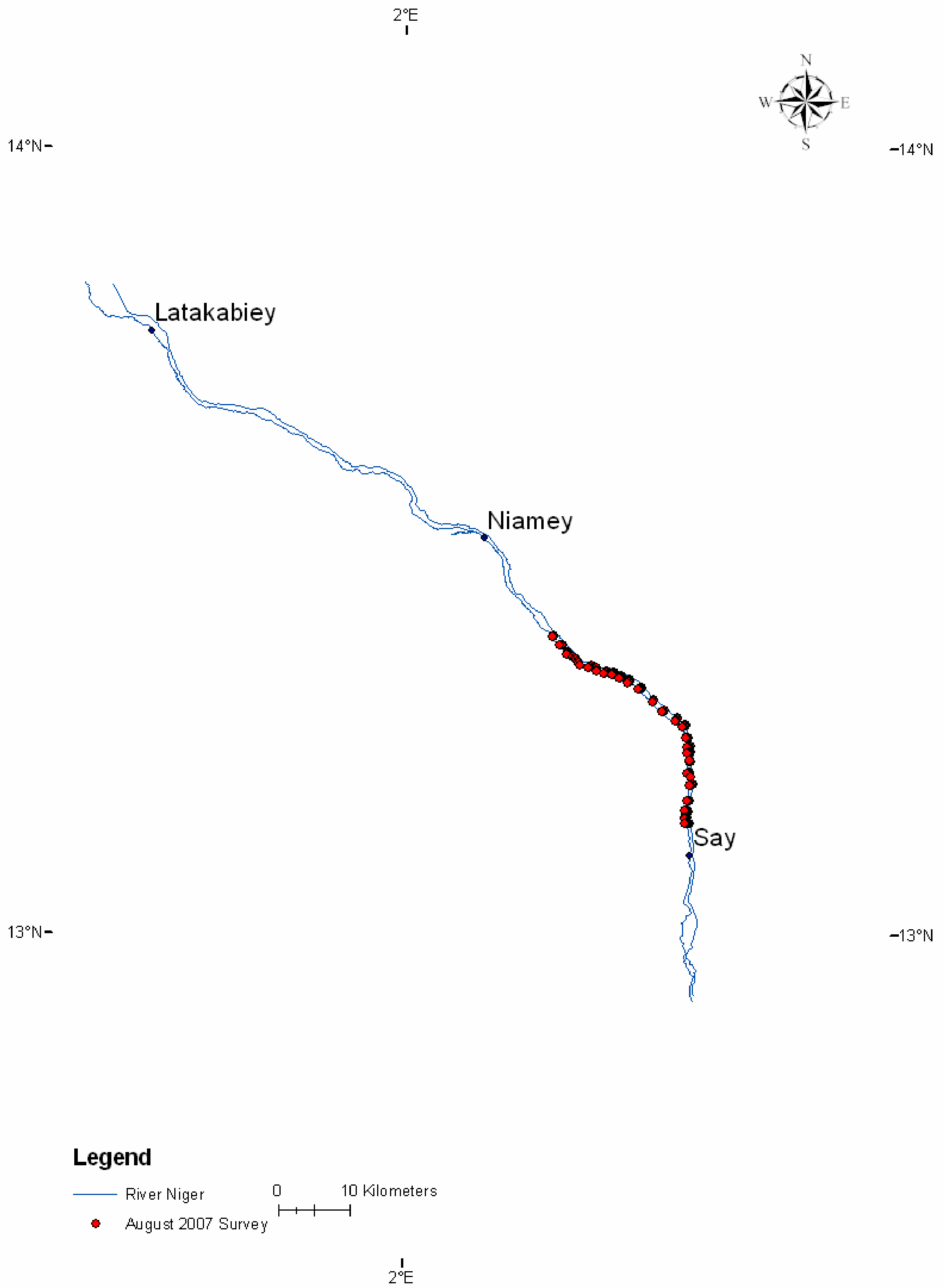


Figure II- 21: Bed level survey area of reach 2

In Figure II- 22 and Figure II- 24, positive y-axis values represent accretion and negative values represent incision.

Net accretion occurred in the reach 2 portion between 1978 and 2007 (see Figure II- 22).

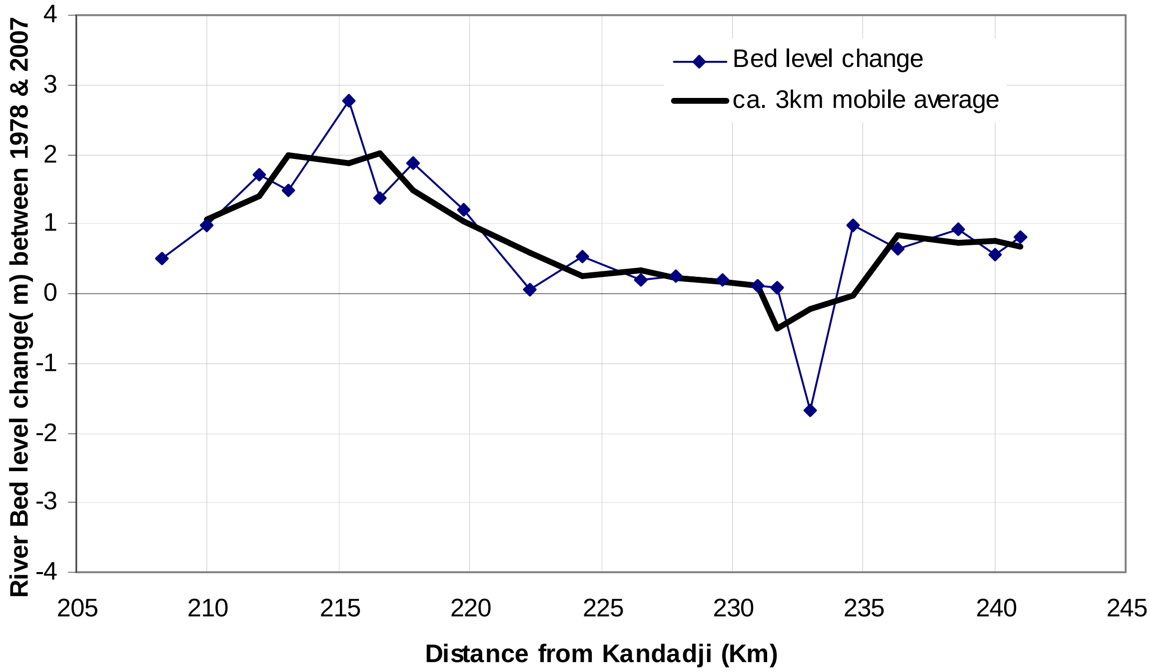


Figure II- 22: Bed level change in a section of reach 2 shown in Figure II- 21

Mean vertical accretion of about 0.74 m occurred in reach 2 of the middle Niger River bed just downstream of Niamey

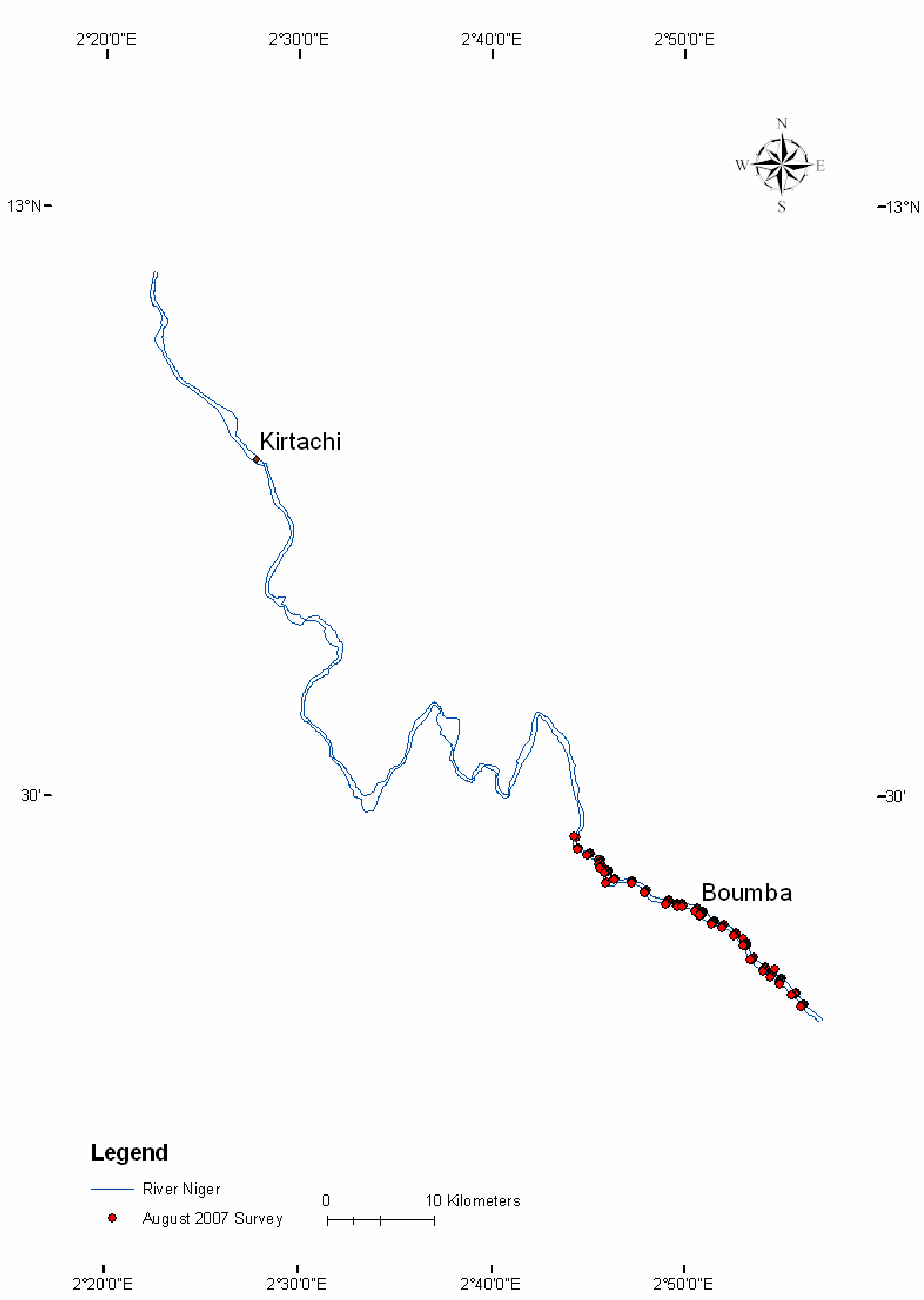


Figure II- 23: Bed level survey area of reach 3

A plot of riverbed level change between 1978 and 2007 for reach 3 is presented in Figure II- 24 showing the area around the River Mékrou confluence with the Niger This stretch of the Niger river shows variable bed level change with considerable areas of bed incision. This could be due to the limited upstream supply of sediment and relative confinement of the river's bank in this reach.

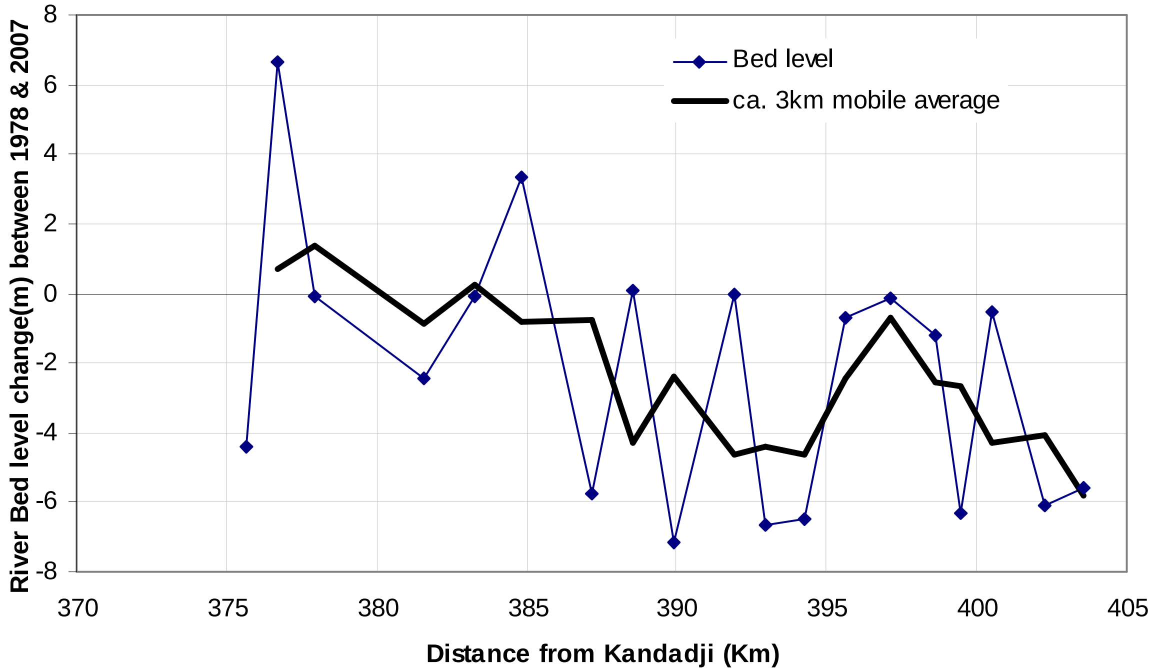


Figure II- 24: Bed level change in a section of reach 3 shown in Figure II- 23

3.4. Summary

While the analyses presented here is not by any means of high precision, it provides a synoptic idea of the changes that have occurred to the Niger River's plan form between 1965 and 1999 and the bed level changes between 1978 and 2007.

- In reach 2, downstream of Niamey, net accretion was observed.
- In reach 3, downstream of the Mékrou-Niger confluence, incision was observed.

4. General conclusions

- The following comments about the analyses of river channel form can be made:
    - Significant channel migration was not observed in the middle Niger River, which is in near natural conditions in terms of river embankments.
    - The usefulness of Geographic Information systems (GIS) for the accurate assessment of historic river planform change using multi-source satellite imagery has been demonstrated.
- The most important river form changes in the study area between 1973 and 1999 are summarized below.
    - Anabranching followed by bank erosion were the major forms of channel response to floods in the middle Niger River. Wende and Nanson [1998] posited that low relief, within-channel vegetation, and a semi-arid to arid environment such as the Sahelian reaches 1 and 2, with declining flow discharges and increasing sediment concentrations downstream necessitate anabranches.
    - For all three reaches studied, the period around 1984 corresponding to decreasing discharge was the period of greatest river channel perturbation. This was caused mainly by the significant floods that occurred before 1984.
    - River channel change occurs slowly in the middle Niger River; sometimes exhibiting time lags between the occurrence of forcing factors and channel response.
    - Floods above about 1900 m^3/s or with a return period greater than 5 years were observed to play an important role in the shaping of channel planform in the middle Niger River.
- In addition to the Niger's tributaries, the ephemeral streams that are characteristic of the area around Niamey have been identified as an important source of sediment supply to the Niger.
- Riverbed accretion and incision patterns have been demonstrated along the middle Niger River for two stretches of the Niger River.

The effects of tributary contribution on the sediment and water discharge of the middle Niger River is discussed in part IV and part V of this work.

Part III – Land cover change in the Middle Niger basin

Land cover changes can be local or widespread in scale and may be monitored by ground observation or by remotely sensed data. The environmental consequences of land cover change are numerous, and may have feedback effects on climate as proposed by Charney [1975].

In order to understand the land cover dynamics of the study area with respect to climatic variability and human impacts, it was necessary to evaluate the land cover changes that occurred as far back as the availability of remotely sensed data permits.

Remotely sensed imagery provides a means for observing and monitoring large areas from the river reach scale to the basin scale, that would otherwise be difficult, time consuming and expensive.

Remote sensing is used to investigate land surface change based on the premise that such changes result in changes in radiance values [*J F Mas*, 1999]. The quantity and quality of the reflected radiation received by satellite sensors is dependent upon the abundance, composition and condition of such land surface components as vegetation, soil, or water [*J Rogan et al.*, 2002].

The aim of this part of the study was to characterize the vegetation and bare soil dynamics over a ~30 year period by remote sensing methods in order to evaluate the propensity for sediment production and transport in the study area.

The objectives include:

- Reviewing the literature on the effects of Sahelian land cover change
- Quantifying the land cover changes that have occurred in the study area
- Comparing the land cover changes of three sub-basins in the study area
- Discussing the possible impacts on erosion and sediment transport.

1. Monitoring land cover change

Remote sensing involves observing the earth's surface, or measuring its characteristics without being in direct contact with it. This is achieved by recording the reflected or emitted energy, which is processed and analysed in a variety of ways. The satellites and sensors used vary in terms of spectral resolution (the sensor's ability to differentiate electromagnetic radiations of different wavelength intervals), radiometric resolution (the sensor's sensitivity to the magnitude of radiated energy), spatial resolution (refers to the smallest possible feature that can be detected), temporal resolution (the revisit period of a remote sensing system to image the exact same area at the same viewing angle) as well as the scene size. In its most basic form, remote sensing requires a source of energy and a radiance response from the surface being observed.

1.1. Methods and tools for land use and land cover monitoring

The instruments or sensors for measuring or detecting the reflected or emitted energy from the target surface require a platform that may be located within or outside the earth's atmosphere. These sensors could be placed on the ground, on aircraft or on satellites that revolve round the earth.

Data collected by many different satellites and sensors have been applied for various earth surface monitoring applications; such as high resolution data collected by satellites and programs launched specifically to provide earth surface observation data such as LANDSAT managed by the U.S. Geological Survey, the "Système Pour l'Observation de la Terre" (SPOT) designed and launched by the Centre National d'études Spatiales (CNES) of France and the Indian Remote Sensing (IRS) series. These satellites are equipped with different multi-spectral sensors and vary in terms of the ground resolution, temporal resolution, and the scene size of the imagery they capture.

There exist other satellite systems originally set up as photo reconnaissance satellites that have now been declassified including the Corona, Argon and Lanyard programs.

Aerial photographs have been commonplace since the 1920s and 1930s and therefore remain a powerful tool for land use/land cover change detection [*A D Cameron et al.*, 2000; *J Nachtergaele and J Poesen*, 1999], gully erosion [*J Nachtergaele and J Poesen*, 1999] river channel morphology [*V Vanacker et al.*, 2005]

Winterbottom and Gilvear [1997] used airborne multi spectral imagery and aerial photography for a three-dimensional river channel morphology by correlating reflectance levels with water depth.

Low-resolution data have also been useful for monitoring land surface changes; the Advanced Very High Resolution Radiometer (AVHRR) operated by the National Oceanic and Atmospheric Administration is one of several such sensors. AVHRR data cover much larger areas at a coarse resolution of 1.1 km. Such low-resolution data covering large areas is commonly used in drought monitoring studies [*A Anyamba and C J Tucker*, 2005; *A Bonfiglio et al.*, 2002; *P Diello et al.*, 2005; *A Diouf and E F Lambin*, 2001; *S E Nicholson et al.*, 1990]

Remote sensing using multi-spectral imagery has been used to map erosion and accretion patterns [*M El-Raey et al.*, 1999; *O E Frihy et al.*, 1998; *K White and H M El Asmar*, 1999] , stream morphology [*A Wright et al.*, 2000]. Suspended sediment concentration can also be estimated from statistical relationships between field-measured suspended sediment concentration and satellite measured spectral reflectance [*S M J Baban*, 1995; *D Doxoran et al.*, 2002; *M D Nellis et al.*, 1998; *W Zhou et al.*, 2006].

Suspended sediment concentration can also be estimated from statistical relationships between field-measured suspended sediment concentration and satellite measured spectral reflectance using Landsat [*S M J Baban*, 1995; *M D Nellis et al.*, 1998; *W Zhou et al.*, 2006] and SPOT [*D Doxoran et al.*, 2002] imagery.

Radar has also been used to estimate river stage and discharge in combination with topographic data [*L C Smith*, 1997].

1.1.1. Tools

Landsat and Corona imagery, two major types of data that have been used to monitor land cover change will be briefly presented.

1.1.1.1. LANDSAT imagery

The Landsat program, originally known as the Earth Resources Technology Satellite (ERTS) program, began to provide multi spectral images of the earth in 1972 and has continued until the present time. Landsat 1 was launched in July 1972 and Landsat 7 is the latest satellite in the series. The capabilities of these satellites have been greatly improved over time. Several imaging instruments have been flown on the Landsat satellites. The Return Beam Vidicon (RBV) sensor was flown on the first three missions, together with a Multi- Spectral Scanner (MSS) sensor.

Landsats -4 and -5 were equipped with an improved version of the MSS along with the Thematic Mapper (TM); however, routine collection of MSS data was terminated in 1992.

Landsat -6 carried an "Enhanced Thematic Mapper" only, and Landsat -7 is equipped with an "Enhanced Thematic Mapper-plus" (ETM+).

TM and ETM+ data include a thermal infrared ban; band 6. The ETM+ sensor includes an additional panchromatic band (band 8).

The key characteristics of the Landsat program [*USGS*, 2005; 2006; *USGS and NOAA*, 1984] are listed in Table C- 1 to Table C- 4 (See appendix C).

The long life span of the Landsat program as well as its high resolution and good spatial coverage make it well suited for long term monitoring and research. Lauer et al. (1997) discuss the evolution of the Landsat program.

Cooley and Turner [1982] evaluated the application of Landsat imagery for monitoring transient environmental changes in the Sahel. They highlighted the use of Landsat imagery for the mapping of accelerated erosion in the Sahel region with the lightest areas on the images indicating severe erosion activity according to on-site inspection.

1.1.1.2. CORONA Imagery

In 1995, the United States government declassified CORONA satellite imagery collected between 1960 and 1972. The ground resolution of the imagery acquired during the CORONA program improved from 8 meters to 2 meters [*National Reconnaissance Office NRO*].

The availability of Corona imagery extends our ability to assess land surface conditions using high-resolution imagery to the 1960s (a decade before the availability of commercial satellite imagery). Corona imagery have been used, in combination with more recent satellite imagery to study land use and land cover change [*J Liu et al.*, 2001; *O Rigina*, 2003; *G G Tappan et al.*, 2000], as an aid in archaeological prospection [*M J F Fowler*, 2004; R *Goosens et al.*, 2006], for geological [*H Lorenz*, 2004] and peri-glacial geomorphology [*G Grosse et al.*, 2005]. Corona images provide enough detail to detect individual trees [*G L Andersen*, 2006].

Early Corona systems carried a single panoramic camera, or a single frame camera, while later systems carried two panoramic cameras looking 30 degrees apart (a forward-looking camera and an afterward-looking camera). Occasionally one of the pair of cameras malfunctioned or was programmed to halt, while the other continued to operate [*USGS*, 1996].

Goosens et al. [2006] pointed out the importance of stereoscopic viewing of the Corona imagery for archaeological applications. The combination of stereoscopic images helps to give the effect of solidity or depth, and thus, can be used for relief mapping and three-dimensional interpretation of landscape, where available.

Corona images have digital values that range from zero (black) to 255 (white), with coherent dark pixels representing low reflection and high absorption of sunlight, the grey-scale values are correlated to surface reflectance. The Corona images are thus well suited to visual interpretation as water (high absorption) and barren land (high reflectance) as well variations in soil and vegetation moisture can be discriminated.[*G Grosse et al.*, 2005].

The major drawback of Corona images appears to be the fact that they contain geometric distortions; this is especially true for images of mountainous regions.

In addition to enlarging the record of land surface monitoring, the spatial coverage and ground resolution of Corona images make them an interesting option for studying historic land surface change.

1.1.2. Processing

One of the most significant applications of remote sensing is to detect and measure change by following the evolution of one or more environmental parameters over a period using multi-temporal datasets.

Procedures that utilise remotely sensed imagery for change detection usually involve three major steps, namely: pre-processing, image analysis, and an accuracy assessment of the results.

1.1.2.1. Pre-processing:

Raw satellite data may not always be “suitable” for use without some calibration or correction. Pre-processing is that phase of data processing where preliminary steps are taken to prepare the raw data for analysis by correcting them for distortions due to sensor noise, platform or atmospheric conditions at the time of acquisition. These distortions are mainly geometric and radiometric.

Geometric correction involves the transformation of data to match spatial relationships on the Earths surface by locating several identifiable ground control points (GCPs) in the raw image and matching them to their true ground coordinates.

Radiometric correction is often required to compare images collected at different times or by different sensors.

Noise in an image is usually caused by sensor response errors during data recording and transmission. The techniques for correcting errors due to noise errors are sensor specific.

The brightness values of the pixels in a satellite image, recorded as digital numbers (DNs) in a binary format depend on the number of bits used to record the data. They are also affected by several factors that are dependent on the specific sensor and atmospheric conditions at the time of data acquisition including the sun elevation angle, interference of atmospheric aerosols, changes in the sensor response over time etc.

The atmospheric correction procedure helps to reduce the error in estimating the surface reflectance or to set a multi-temporal data set to a common radiometric scale [*C Song et al.*, 2001].

Through scattering, atmospheric aerosols increase the apparent reflectance of dark objects and reduce it for bright objects in the image causing a loss of information that cannot be recovered by atmospheric correction. This is because the number of surface reflectance values or corrected DNs will not exceed the number of raw DN levels.

There exist two types of radiometric calibration, namely:

- Absolute radiometric correction: Digital numbers are converted into surface reflectance or radiance. This helps to extract subtle differences in reflectance.
- Relative calibration: This is a process used to remove or normalize the variation within a scene and normalize the intensities between images of the same study area collected on different dates.

Atmospheric correction is unnecessary when:

- Working with a single date image;
- Post-classification is used as the method of change detection;
- Training data are to be derived from the image being classified.

This is because atmospheric correction for a single date image is often equivalent to subtracting a constant from all pixels in a spectral band [*C Song et al.*, 2001].

1.1.2.2. Image analyses

Change detection involves the application of data transformation procedures and analysis techniques to highlight areas of significant change. There exist many change detection techniques from simple visual comparison or interpretation to more sophisticated techniques. Lu et al. [2004] give a summary of change detection techniques that include :

- Algebraic methods: These methods utilize indices, ratios or simple subtraction relationships between two or more spectral bands in order to identify image bands or thresholds of change.
- Classification methods: The results of supervised and unsupervised classification are the basis of these methods.
- Advanced models: These methods convert image reflectance values to physically based parameters through linear or non-linear models.
- Visual Analysis: Includes the visual interpretation of multi-temporal colour composite images and on-screen digitizing of changed areas.
- Other methods: combinations of one or more methods, GIS overlay etc.

1.1.2.3. Accuracy assessment:

The accuracy of change detection analysis is assessed by ancillary data such as ground truth as well as the analyst's familiarity with the study area. Quantitative methods for accuracy testing are based on indices that compare results against known reference data.

The parameters used to assess the accuracy of classification results are:

- Overall accuracy: This is the number of correctly classified pixels as a percentage of the total number of pixels.
- Producer's accuracy (omission error): The producer's accuracy indicates the probability of a reference pixel being correctly classified.
- User's accuracy (commission error): The user's accuracy measures the probability that a pixel classified on the map/image actually represents that pixel on the ground.
- The kappa statistic describes agreement achieved beyond chance, as a proportion of that agreement which is possible beyond chance [*Rogan et al. 2003*].

1.2. Data and methods applied in this study

A multi-temporal and multi sensor data set that included Landsat (MSS, TM, and ETM+) and Corona satellite imagery was used for this study. The characteristics of the imagery used are presented in Table III- 1. The Landsat images range from the mid-1970s to 1999, while the

Corona imagery are used in an attempt to extend the remotely sensed information to the pre-1970 period i.e. the period before the drought.

The Landsat images cover four periods around 1975, 1984, 1990, and 1999.

One major difficulty in assessing the land use changes for the three tributary basins between the 1970s and 1999 was the difficulty in acquiring images that covered the entire basin areas for the four periods. The images for the period around 1999 are the only complete mosaics for the three tributary basins. The multi-temporal comparison is therefore made between successively smaller basin areas for the periods around 1984 and 1975 with the assumption that these smaller areas largely represent the basin conditions for the periods considered.

A second drawback of the analyses may be the dates of imagery particularly for images acquired in mid October when the effect of the rainy season may still be in effect particularly in the southern part of the study area.

Table III- 1: Summary of satellite data used in the study

Sensor	Scene ID or Path/Row	Acquisition Date
CORONA	DS 1025-2122DF (049 to 052)	13 OCTOBER 1965
LANDSAT 1 MSS	206/052* 207/052*	17 OCTOBER 1973 18 OCTOBER 1973
LANDSAT 2 MSS	207/051*	22 NOVEMBER 1975
LANDSAT 3 MSS	208/050*	29 NOVEMBER 1979
LANDSAT 4 TM	194/050* 193/051*	18 OCTOBER 1992 20 NOVEMBER 1989
LANDSAT 5 TM	194/050 193/051 192/051	05 NOVEMBER 1984 14 NOVEMBER 1984 07 NOVEMBER 1984
LANDSAT 7 ETM+	195/049 195/050 195/051 194/050 194/051 194/052 193/053 193/051* 192/051* 192/052 192/053	29 OCTOBER 1999 29 OCTOBER 1999 13 OCTOBER 1999 22 OCTOBER 1999 11 OCTOBER 2001 7 NOVEMBER 1999 20 OCTOBER 2000 31 OCTOBER 1999 9 NOVEMBER 1999 26 OCTOBER 2000 26 OCTOBER 2000

**Source for this data set was the Global Land Cover Facility,www.landcover.org.*

All other data was provided by the Centre Regional Agrhymet

Data from GLCF was received as MSS 57 meter resolution, TM and ETM+ 28.5 meter resolution.

1.2.1. Corona imagery

Four parallel strips from the DS 1025-2122DF scene that covered parts of the middle Niger River basin were acquired. The images were captured by the KH-4A system in October 1965 (see Table III- 1). The images were provided as film positives by the "Centre regional Agrhymet, Niamey" in a digital format 319MB (x 4 files) per scene, scanned at 3600dpi.. This set of Corona images were the only ones available that could be compared with more recent imagery as they were acquired in October.

Where necessary the four files were re-assembled by selecting 6 to 8 tie points on overlapping sections of the files.

The image strips were radiometrically calibrated by a dark subtract algorithm with ENVI 4.2 software.

30 ground control points (GCPs) were identified on the Corona scene mosaic (see Figure III- 1:) for co-registration with the Landsat ETM+ imagery (path 193 row 051). The image mosaics were then rectified to the WGS 1984 datum, zone 31N, with a second-order polynomial warping function and cubic convolution resampling to 6 m pixels (see Figure III- 2). The RMS error for rectifying the CORONA mosaic was 27.98 m, less than 1 pixel.

The resulting image was then classified using a combination of unsupervised classification and visual interpretation. A post-classification comparison was made of Corona and Landsat data using a subset of the same area. Although the Corona imagery covers only a minor part of the Sirba basin, it was analysed to gain pre-Landsat information about the study area and to test it's applicability to land cover change detection. The location of the image covered by the Corona mosaic (2840 km²) is indicated in Figure C- 18(appendix C) with respect to the study area. The results of the land cover analysis are presented in Figure C- 19 and Figure C- 20 of appendix C and are in agreement with the results to be presented in the following sections for the Gorouol and Sirba Sahelian basins. In particular, the Corona imagery classification confirms the negative impact of the drought that occurred around 1970 on vegetation in the study area.

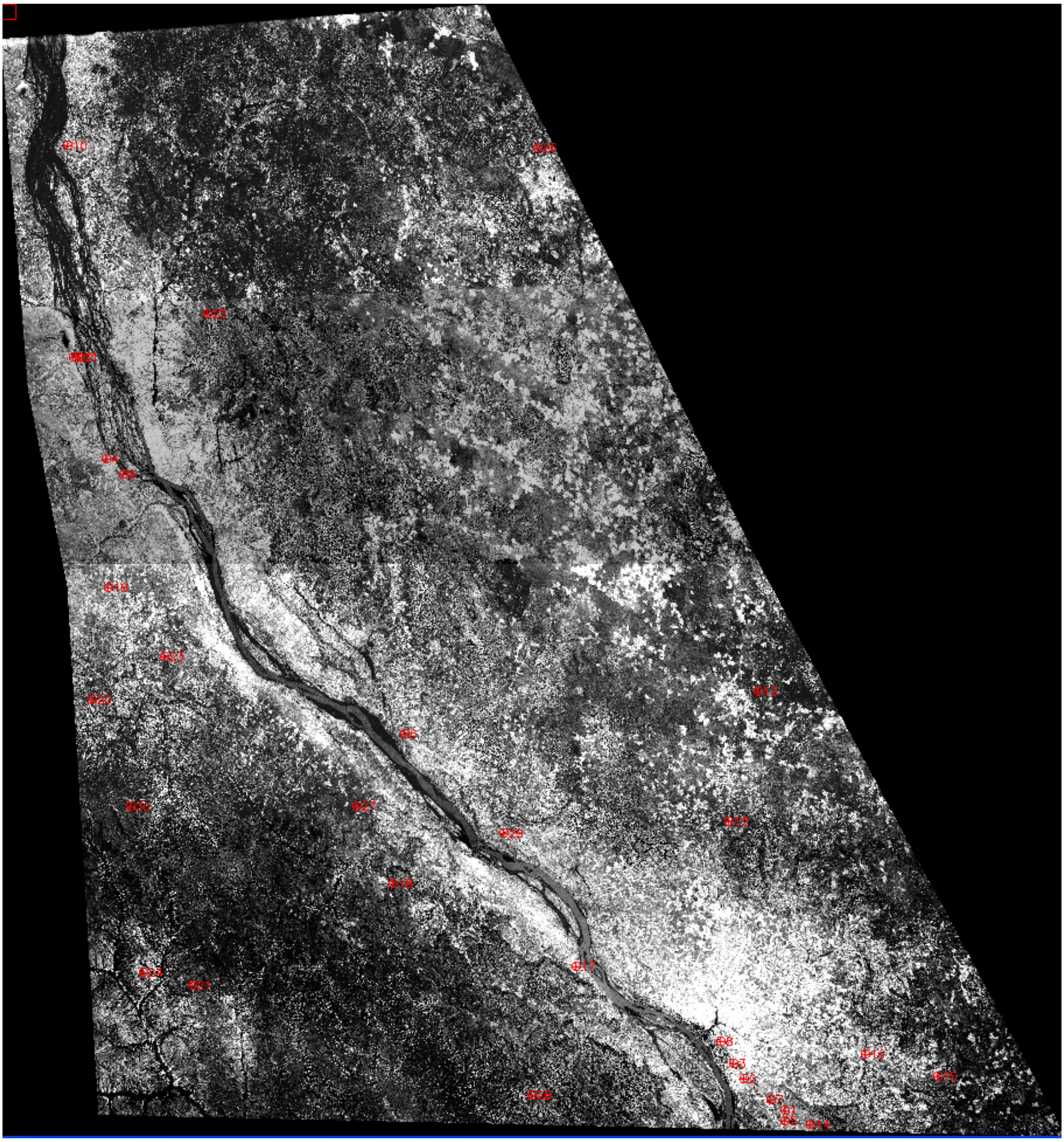


Figure III- 1: Selection of ground control points on the Corona mosaic

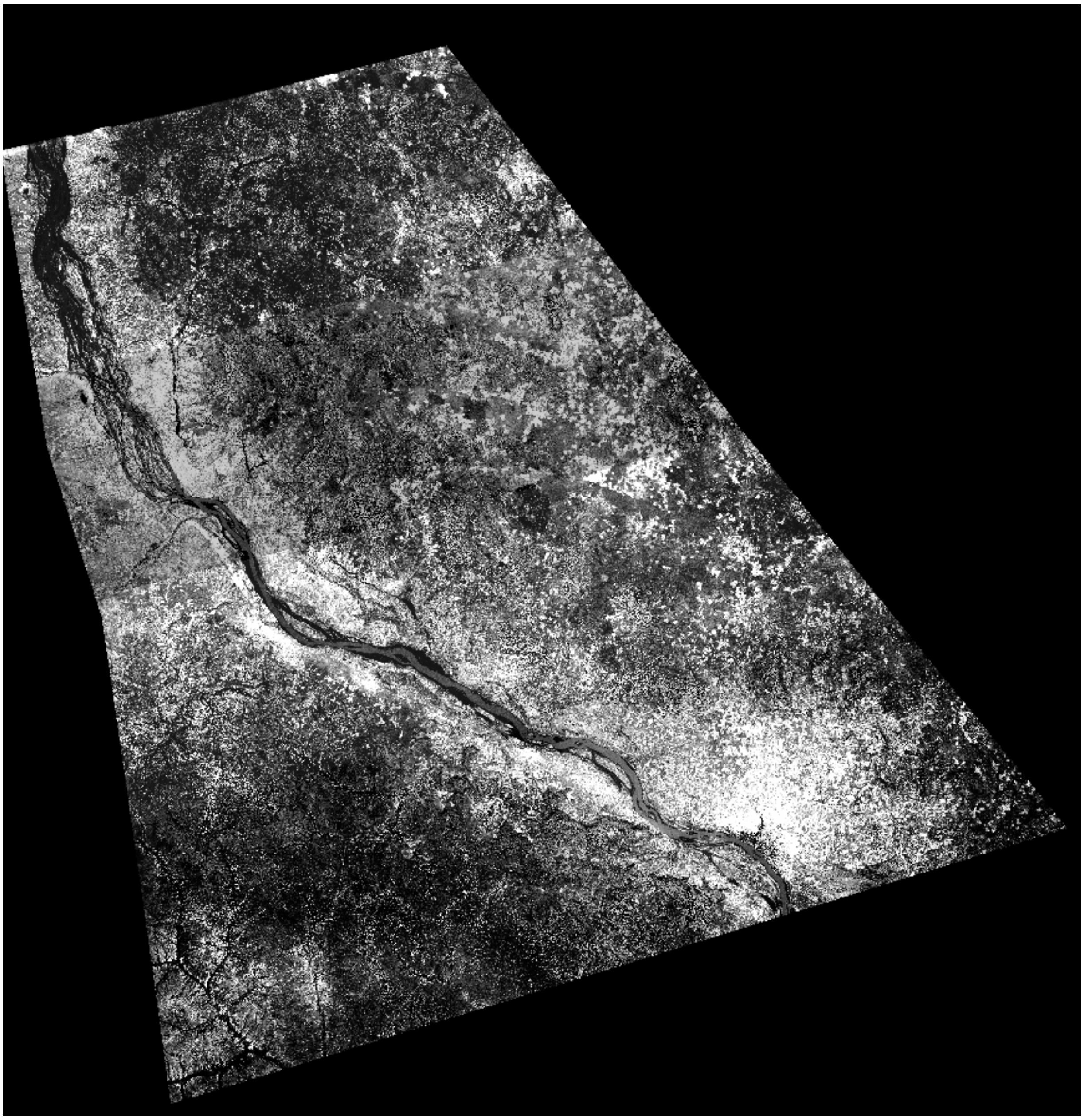


Figure III- 2: Warped Corona mosaic

1.2.2. Landsat imagery

Where possible cloud-free, near anniversary date images were obtained.

In order to obtain a consistent and reliable data set, the available Landsat images were co-registered to the most recent Landsat ETM+ image available for the same area before further enhancement or classification was performed.

Image classification: An unsupervised classification procedure was carried out using the ISODATA method of the ENVI software that classifies pixels by evenly distributed class means in the data space and iteratively clusters the remaining pixels using minimum distance techniques. At each iteration step, the method recalculates means and reclassifies pixels with respect to the new means until the specified pixel change threshold or the specified maximum number of iterations is reached. In other words, pixels are grouped together based on their spectral similarity.

Post-classification involved checking the results of unsupervised classification against visual interpretation from the appropriate false colour composite images or band ratio images as well as field observations of various locations within the study area and combining classes where necessary. The image classification process is schematized in Figure III- 3.

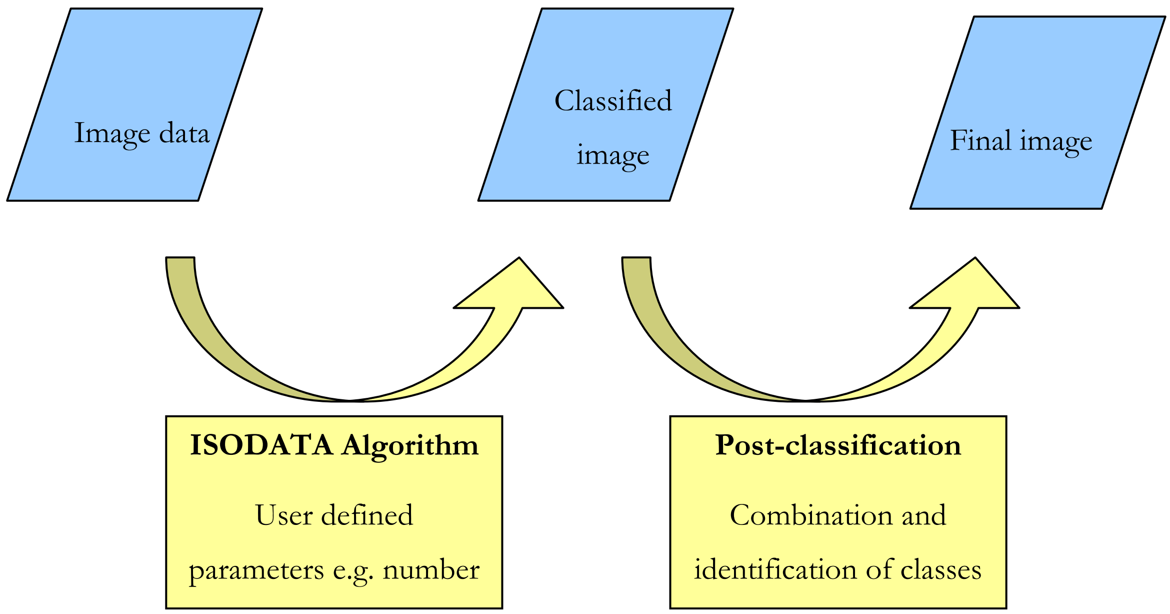


Figure III- 3: Unsupervised classification procedure

For the TM and ETM+ Landsat images, a short-wave infrared (SWIR) composite of bands 7, 4 and 2 (see table C3 and table C4 in appendix for details) was mainly used in the classification and interpretation of classes, because surface albedo in the SWIR portion of the spectrum is determined primarily by moisture content. The SWIR composite is therefore suited for the detection of vegetation stress, as well as soil type s and levels of soil disturbance.

For Landsat MSS images, with a more limited spectral resolution, a near infrared (NIR) composite of bands 7, 5 and 4 (see table C2 in appendix for details) was used for in classification procedure. The NIR composite is primarily suited for studying vegetation because of the high reflectance of chlorophyll in the NIR portion of the spectrum.

The images used for the land cover analysis are near anniversary date images acquired between the end of October and early in November. Considering that planting takes place around July and that the millet crop reaches maturity after 60 to 70 days, the period of October/November is the post-harvest period in the Sahel.

For the purposes of this study, eight land cover classes were considered appropriate for the description of the study area and they are described below: The choices were made based on the ease of identification of classes by visual interpretation after the unsupervised classification algorithm was carried out on all the images. A further reason for the choice of the eight classes was the nature of the study that was concerned with the water resources of the study area in relationship with different states of bare soil and vegetation.

- Bare soil: This corresponds to undifferentiated soil devoid of vegetation cover.

Figure III- 4: Bare soil

- Sandy bare soil: Corresponds to soil that has been recently disturbed such as recently cultivated lands or sediment deposits.

Figure III- 5: Sandy bare soil

- Paved/rocky bare soil: These are bare soils with high reflectivity and include paved roads and infrastructure, but also include crusted/ highly parched bare soils.

Figure III- 6: Paved/rocky bare soil

- Tree: Relatively dense wooded vegetation characterised by a high reflectance of the chlorophyll in the near infrared bands.

Figure III- 7: Trees with high moisture content

- Tree, poor state: This is vegetation with comparatively lower moisture content signifying stressed vegetation or very sparse vegetation.

Figure III- 8: Trees with low moisture content

- Shrubs/Grass: this is land cover dominated by woody plants less than about 1.5 m and grass.

Figure III- 9: Shrubs and grass

* Sediment-laden water: In general, the reflectance of water increases with increasing suspended sediment concentration allowing sediment-laden water to be differentiated from clear water.

Figure III- 10: Shallow sediment-laden water

* Water: Relatively clear and deep water bodies.

Figure III- 11: Clear water

2. Study sub-basins

Land cover changes are presented for the Gorouol, the Sirba and the Mékrou basins in the following sections. The areas of the three study sub-basins were delimited using contour maps of the area from the 1960s. The relative location of the three basins was presented earlier in presenting the study area (see Figure I- 3). Coverage of the entire watersheds for the Gorouol, Sirba and Mékrou rivers was achieved for the most recent period (i.e. 1999/2000) but not for the other periods. One shortcoming of this part of the study was that it was not possible to acquire the images that would have covered the entire basin areas for the earlier periods. Land cover comparison was therefore limited to the areas common to all images with the assumption that these results are applicable to, and representative of the entirety of the three basins.

2.1. The Gorouol Basin

The Gorouol basin has a total basin area of about 45125 km². A classification image of the Gorouol basin for October 1999 is presented in Figure III- 12; it was created from a mosaic of three Landsat scenes (see Table III- 2).

Table III- 2: Landsat scenes used to derive the Gorouol Basin Mosaic for 1999.

Path	Row	Acquisition date
194	50	22 October 1999
195	49	29 October 1999
195	50	29 October 1999

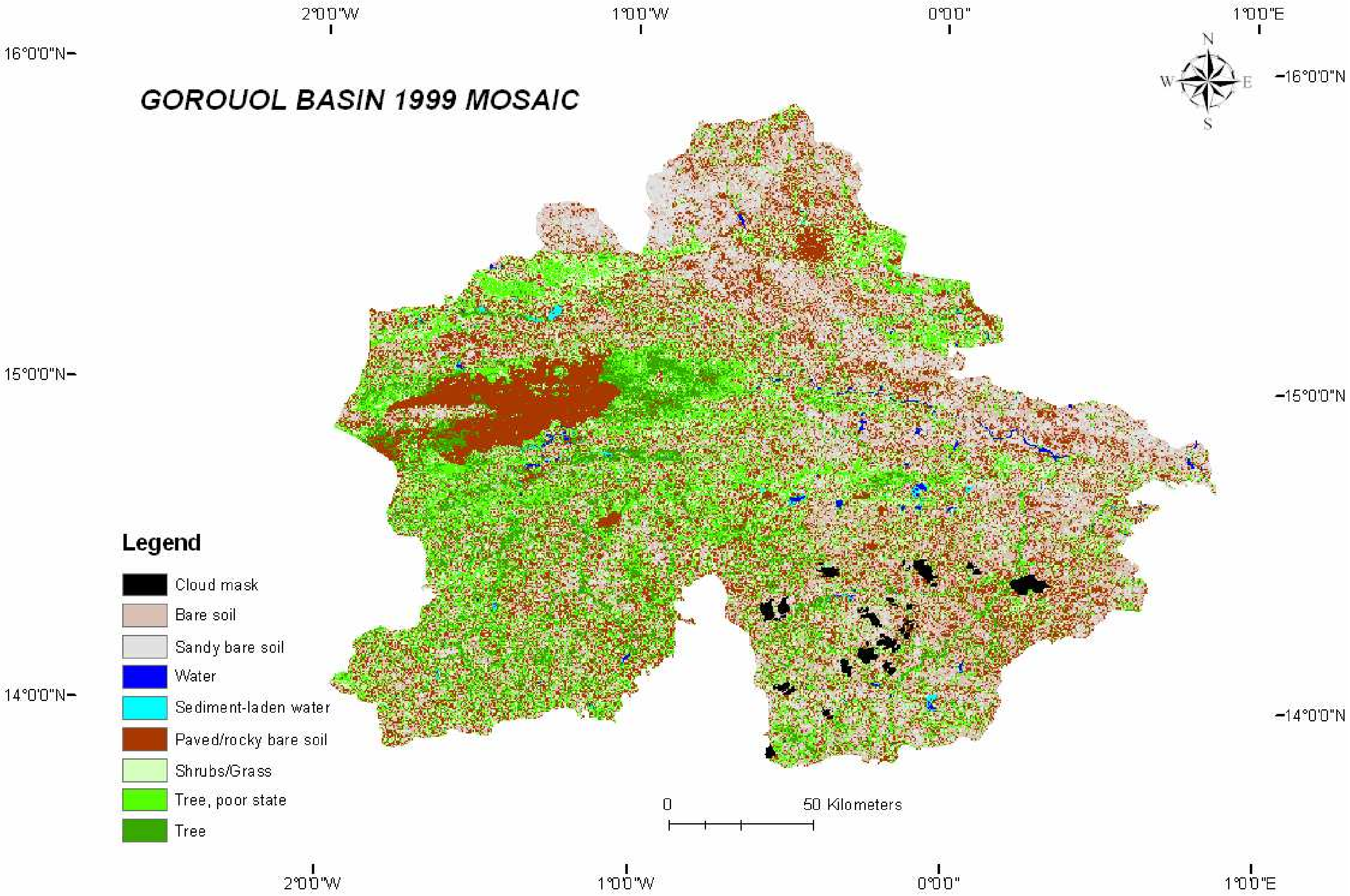


Figure III- 12 : The 1999 Gorouol basin mosaic

The composition of the 1999 mosaic derived for the Gorouol basin is presented in Figure III- 13. The scene acquired on the October 22, 1999 contained some clouds, which represented less than 1% of the total basin area.

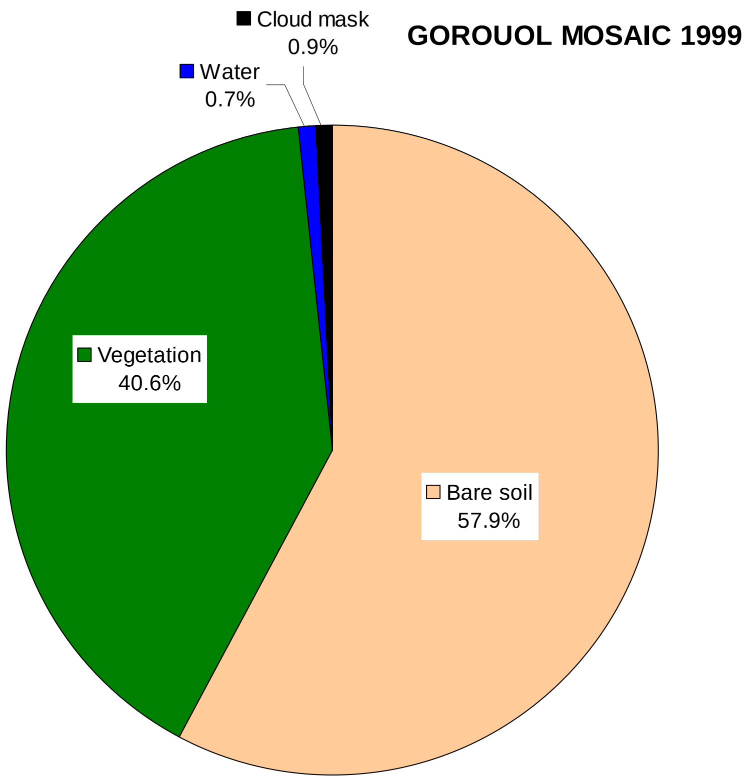


Figure III- 13: Percentage composition of the Gorouol 1999 mosaic

The land cover composition of the entire Gorouol basin in 1999 is presented below in Figure III-14.

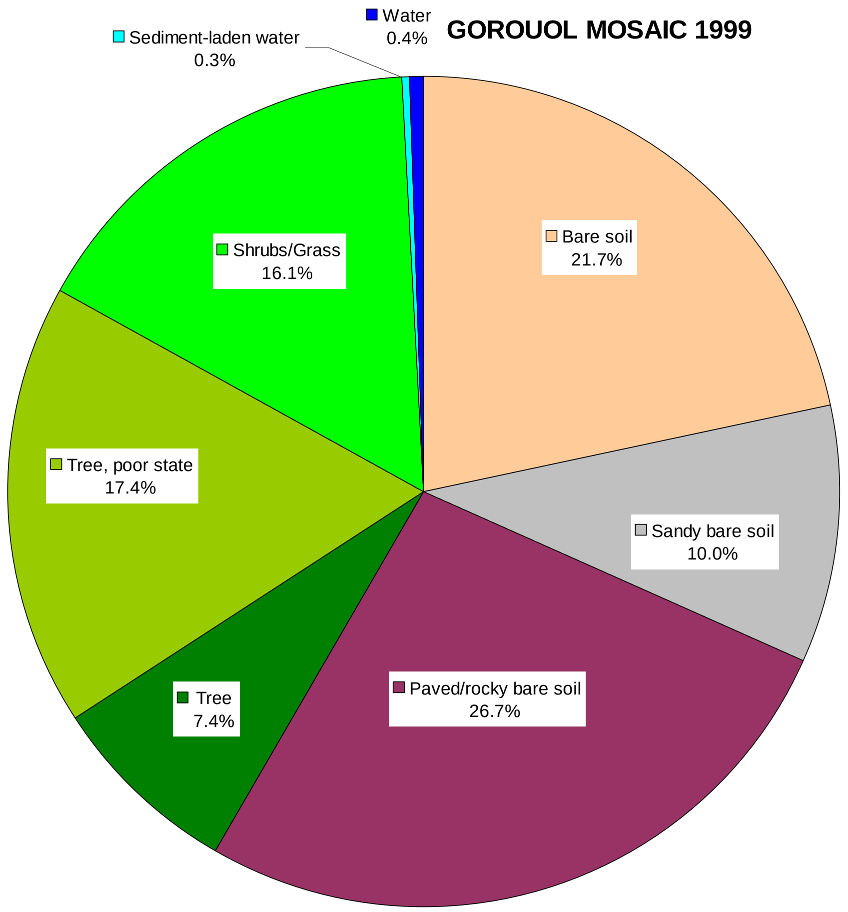


Figure III- 14: Percentage land cover composition for the Gorouol basin in 1999.

2.2. The Sirba basin

The Sirba basin has a total basin area of about 38750 km². The six Landsat scenes that formed the mosaic for the Sirba basin are listed in

Table III- 3. A small portion of a 2001 scene was used to complete the 1999 mosaic.

The classification result of Sirba basin mosaic is presented in Figure III- 15

Table III- 3: Landsat scenes used to derive the Sirba Basin Mosaic for 1999.

Path	Row	Acquisition date
193	51	31 October 1999
194	50	22 October 1999
194	51	11 October 2001
194	52	7 November 1999
195	50	29 October 1999
195	51	13 October 1999

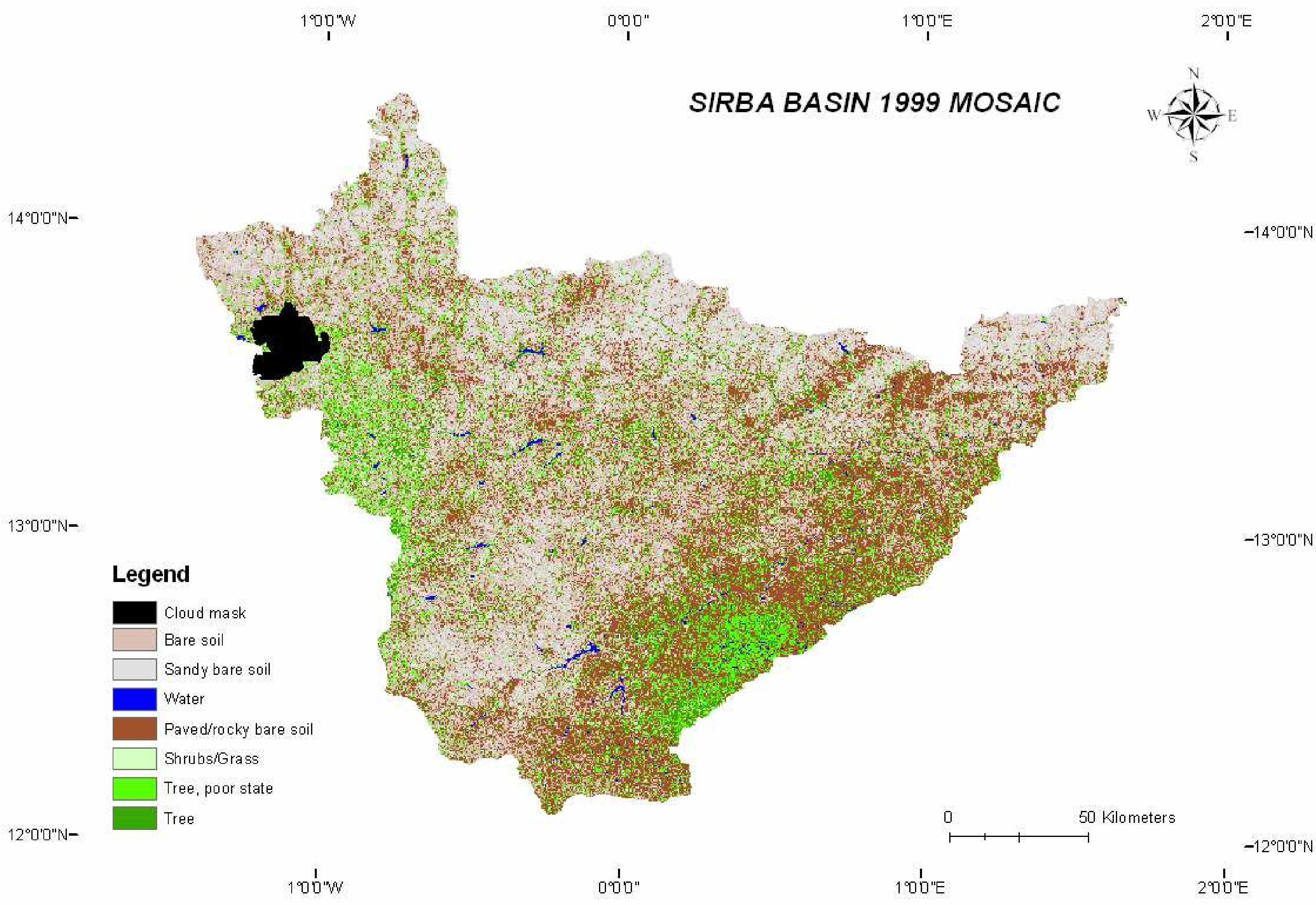


Figure III- 15: The 1999 Sirba basin mosaic

The land cover composition of 1999 mosaic derived for the Sirba basin is presented in Figure III-16. The scene acquired on the October 22, 1999 contained some clouds, which represented 1.3 % of the total basin area.

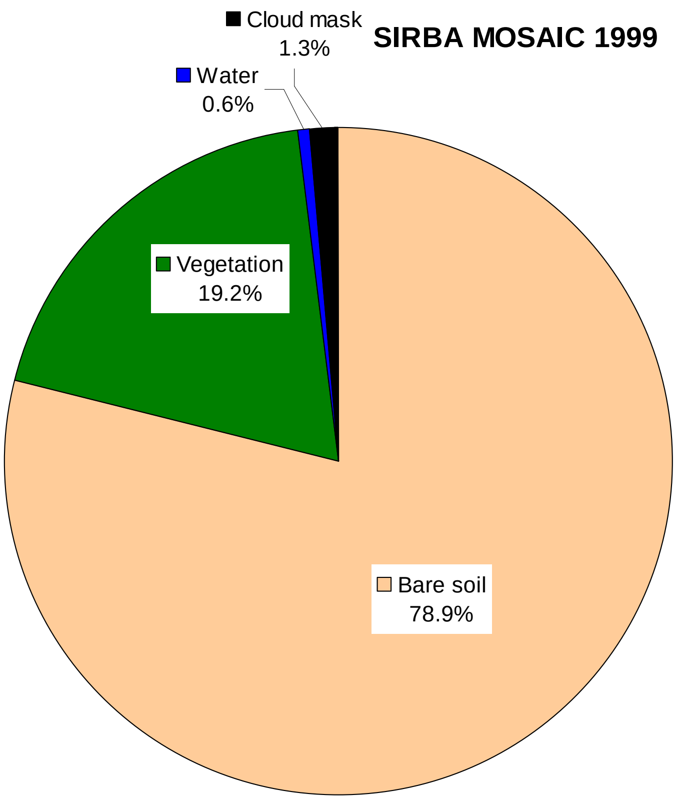


Figure III- 16: Percentage image composition for the Sirba 1999 mosaic

The land cover classes of the Sirba basin in 1999 are presented below in Figure III- 17. In comparison to the Gorouol basin for the same period of 1999, the Sirba basin has more bare surfaces and less vegetation. This is likely due to the more intense anthropogenic influence that results in more cleared lands for agriculture (recall that the cultivated lands are classed as sandy bare soils), the use of trees for fuel wood. The proximity of the Sirba basin to the city of Niamey is also noteworthy. Additionally, the image dates for the Sirba mosaic (from 11 October to 7 November) were later than those used for the Gorouol mosaic (from 22 October to 29 October) and can therefore be expected to be drier.

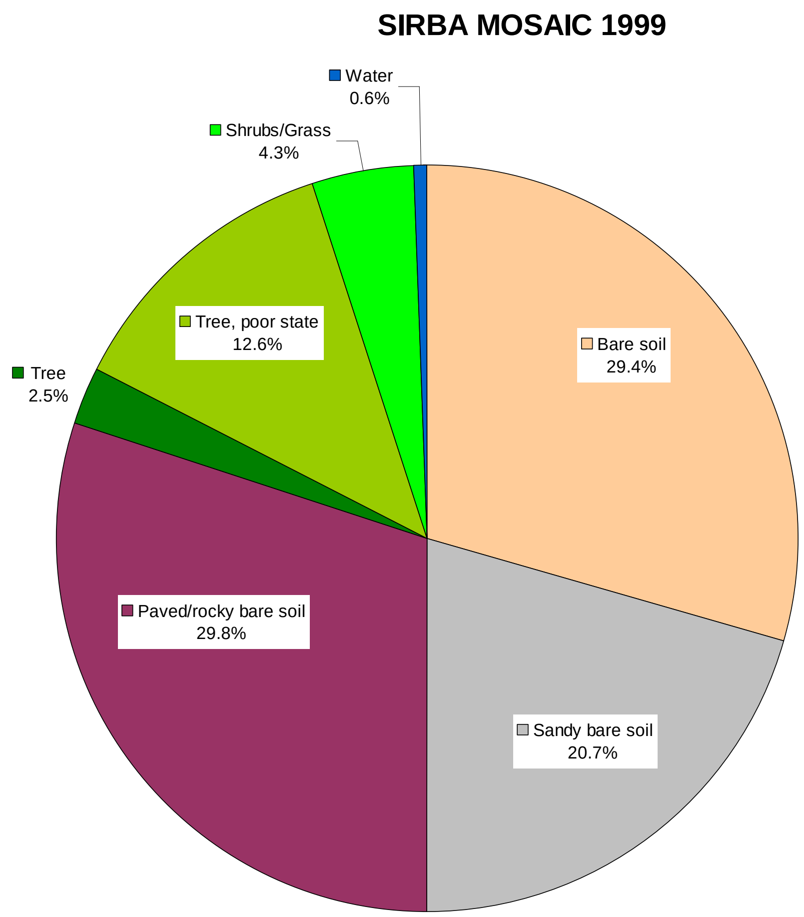


Figure III- 17: Percentage land cover composition for the Sirba basin in 1999.

2.3. The Mékrou basin

The Mékrou basin has a total basin area of about 10690 km². A classification image of the Mékrou basin for October 2000 is presented in Figure III- 18; it was created from a mosaic of three Landsat scenes (see Table III- 4). A small portion of a 1999 scene was included in the mosaic.

The classification result of Mékrou basin mosaic is presented in Figure III- 18.

Table III- 4: Landsat scenes used to derive the Mékrou Basin Mosaic for 1999.

Path	Row	Acquisition date
192	51	9 November 1999
192	52	26 October 2000
192	53	26 October 2000
193	53	20 October 2000

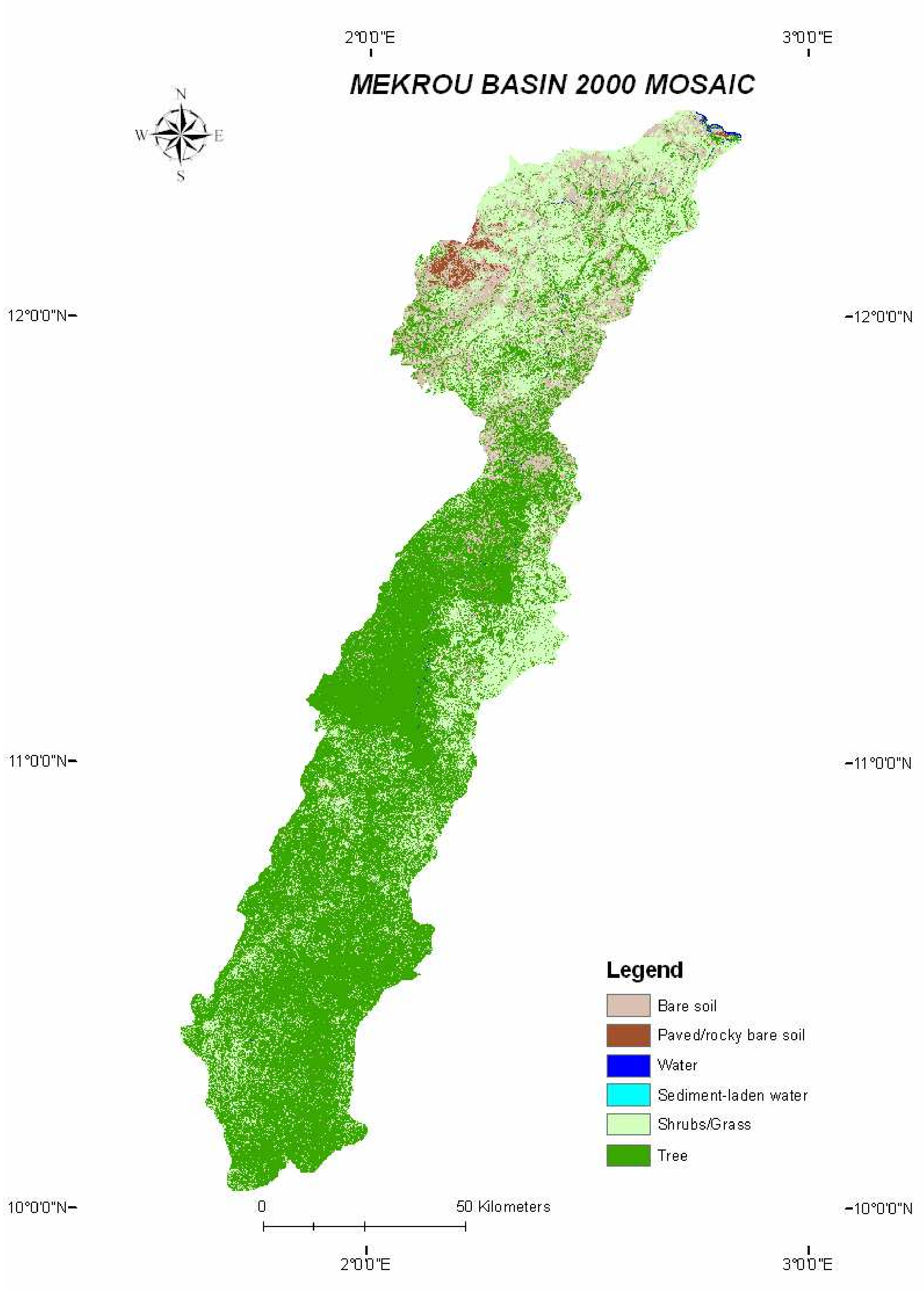


Figure III- 18: The 2000 Mékrou basin mosaic

The composition of 2000 mosaic derived for the Mékrou basin is presented in Figure III- 19. All the scenes used in the mosaic were cloud-free.

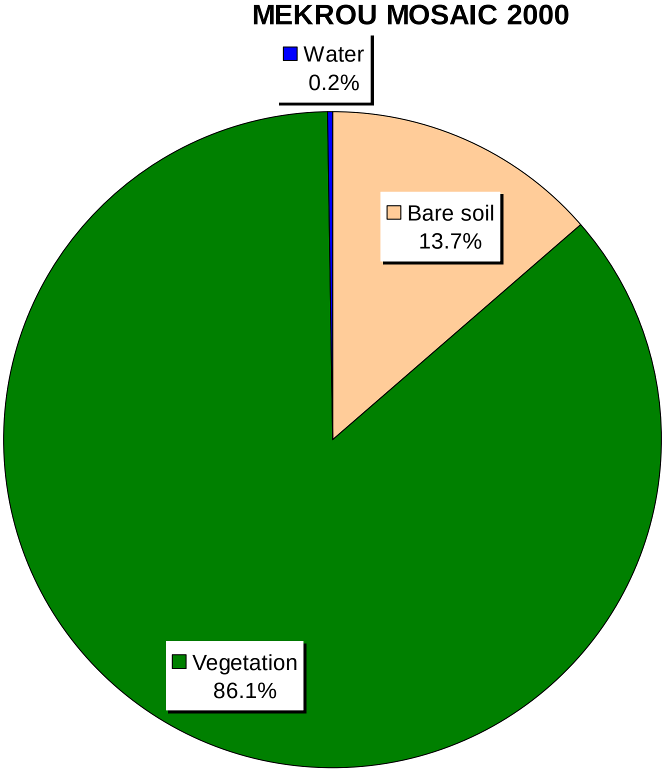


Figure III- 19 : Percentage image composition for the Mékrou basin 2000 mosaic

In stark contrast with the two Sahelian basins (the Gorouol and the Sirba), the Mékrou basin has a high percentage of vegetation cover.

The land cover classes of the Mékrou basin in 2000 are presented below in Figure III- 20 with six classes and not eight like the Gorouol and Sirba basins. The "sandy bare soil" and "tree, poor state" classes are not included because they were not found in the Mékrou basin.

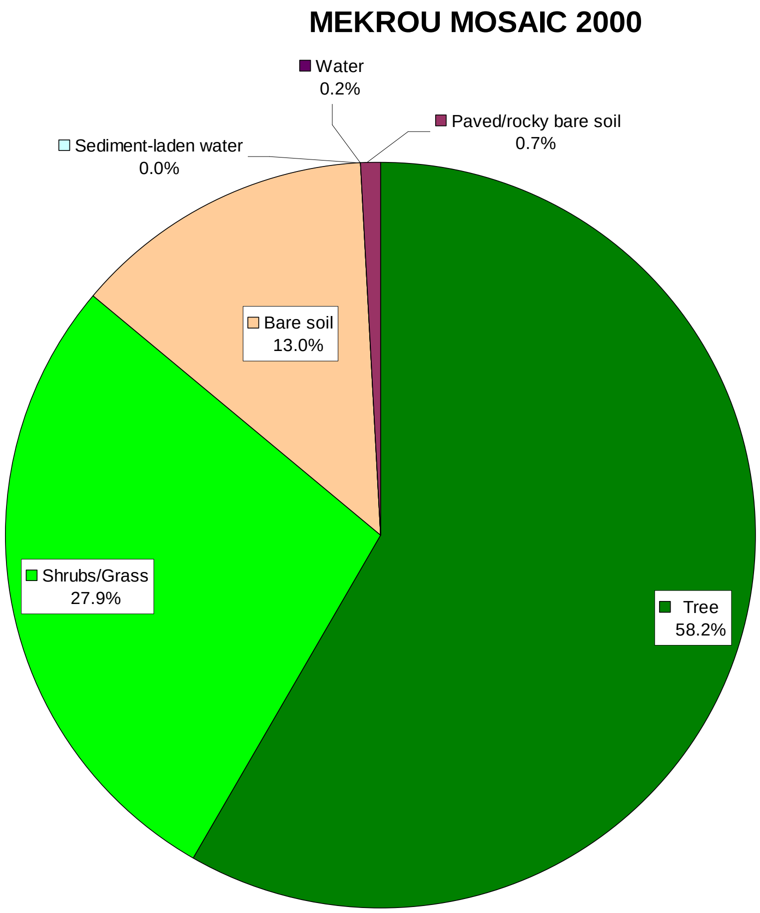


Figure III- 20: Percentage land cover composition for the Mékrou basin in 2000.

3. Results and discussion

3.1. Accuracy assessment

The accuracy of the classification results was evaluated with a confusion matrix comparing historical topographical maps of the region and field surveys to the classification results. The available topographical maps of the region from which land cover information could be used to compare with the classification were maps produced by **IGN** in 1959 for most of the study region and 1980 for the Niamey area. The field surveys consisted of noting and photographing the different land cover types across the study area and their locations with a Geographic Positioning System. In general, the ground truth information obtained from the maps did not provide data for all the land cover classes pertinent to this study.

- The accuracy of the Gorouol basin image of 1979 was assessed based on the 1959 IGN topographical maps for the bare soil, water, tree and tree poor state classes. The accuracy of the other Gorouol images of 1984, 1992 and 1999 were assessed on the basis field observations made in 2006 and 2007 for all the classes.
- The 1980 IGN topographical maps were used to assess the 1975 and 1984 Sirba basin images for the bare soil, paved/rocky bare soil, water, shrubs/grass, tree, and tree poor state classes. The accuracy of the Sirba basin images of 1989 and 1999 were assessed on the basis field observations made in 2006 and 2007 for all the classes.
- The accuracy of the two Mékrou basin mosaics was assessed based on 1959 IGN maps for the area for the bare soil, water and tree classes only.

The overall accuracy and kappa coefficients obtained are presented in Table III- 5 and the confusion matrices for the classification results are in appendix C. (Table C- 6 to Table C- 15)

The results show relatively good accuracy when compared with ground truth data obtained around the time of the image acquisition date.

Table III- 5: Accuracy assessment for the classification results

Basin	Year	Overall accuracy (%)	Kappa coefficient
Gorouol	1979	84.43	0.77
	1984	20.00	0.05
	1992	55.65	0.40
	1999	96.21	0.95
Sirba	1975	74.53	0.54
	1984	94.5	0.89
	1989	64.8	0.50
	1999	97.27	0.96
Mékrou	1973	90.00	0.70
	2000	89.98	0.18

Although the accuracy assessment of the classification results is not ideal particularly in a rapidly changing environment, because of the time lag between some of the ground truth data and the classification images, the results make it possible to obtain a reasonable evaluation of the land cover dynamics of the study area.

3.2. Land cover change for the three basins

3.2.1. Change in the Gorouol basin between 1979 and 1999 (Area: 4757 km²)

The area common to all the available images (1979, 1984, 1992, and 1999) was only 4757 km² due to the reasons described above in paragraph 2.

The classification results of the Gorouol basin for the four dates are presented in Figure III- 21 to Figure III- 24.

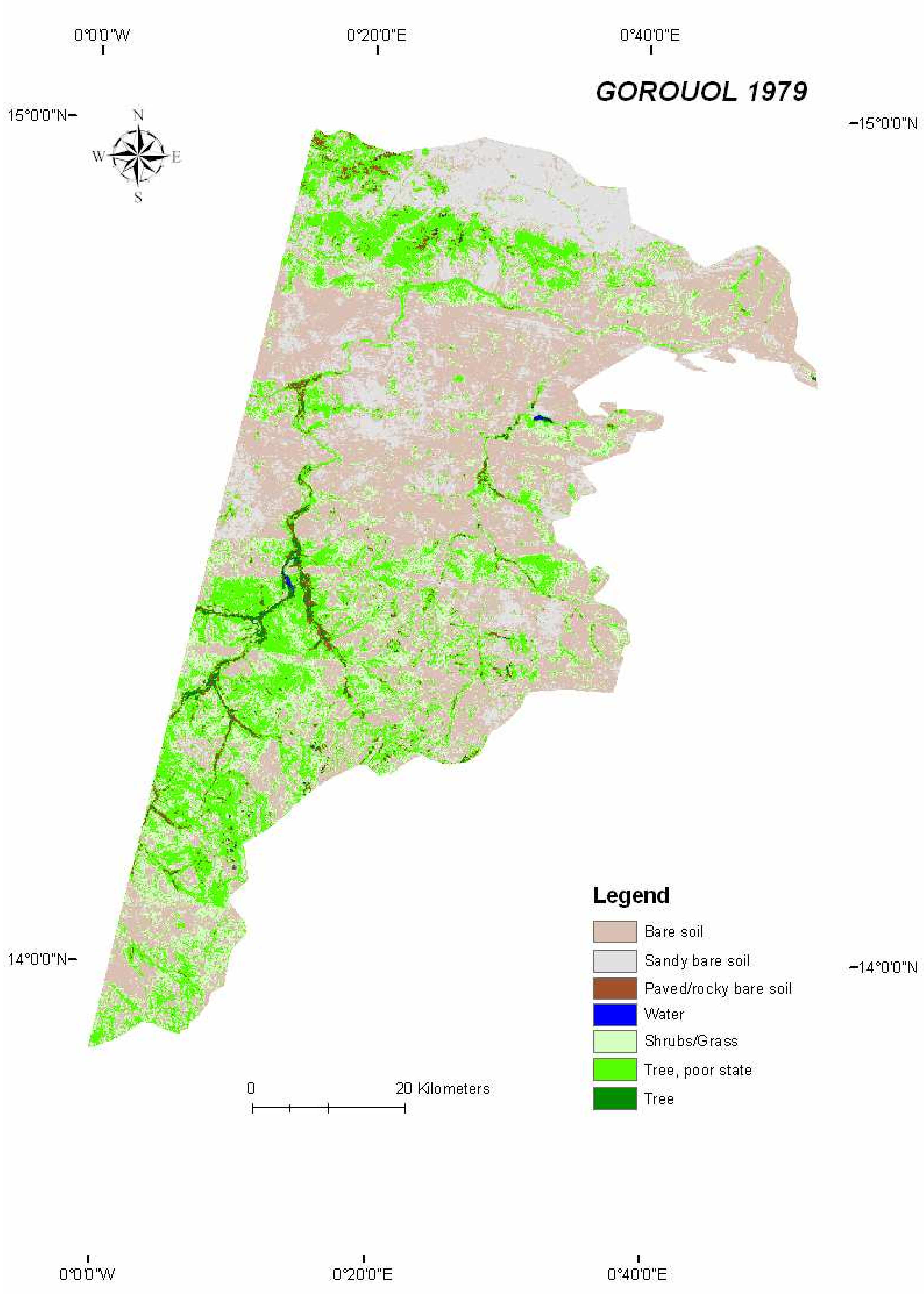


Figure III- 21: Gorouol basin land cover. 29/11/ 1979 (4757 km²)

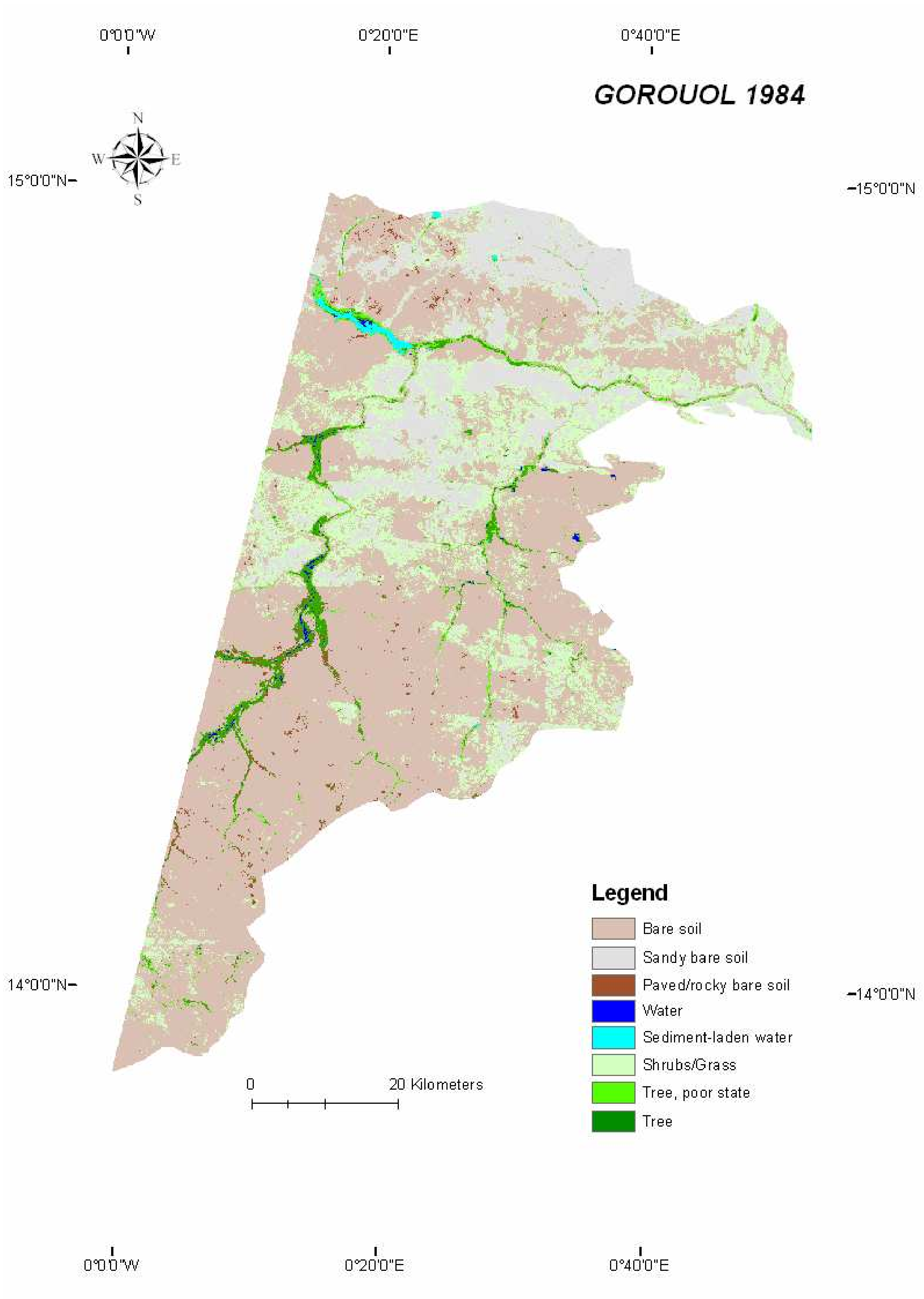


Figure III- 22: Gorouol basin land cover. 05/11/ 1984 (4757 km²)

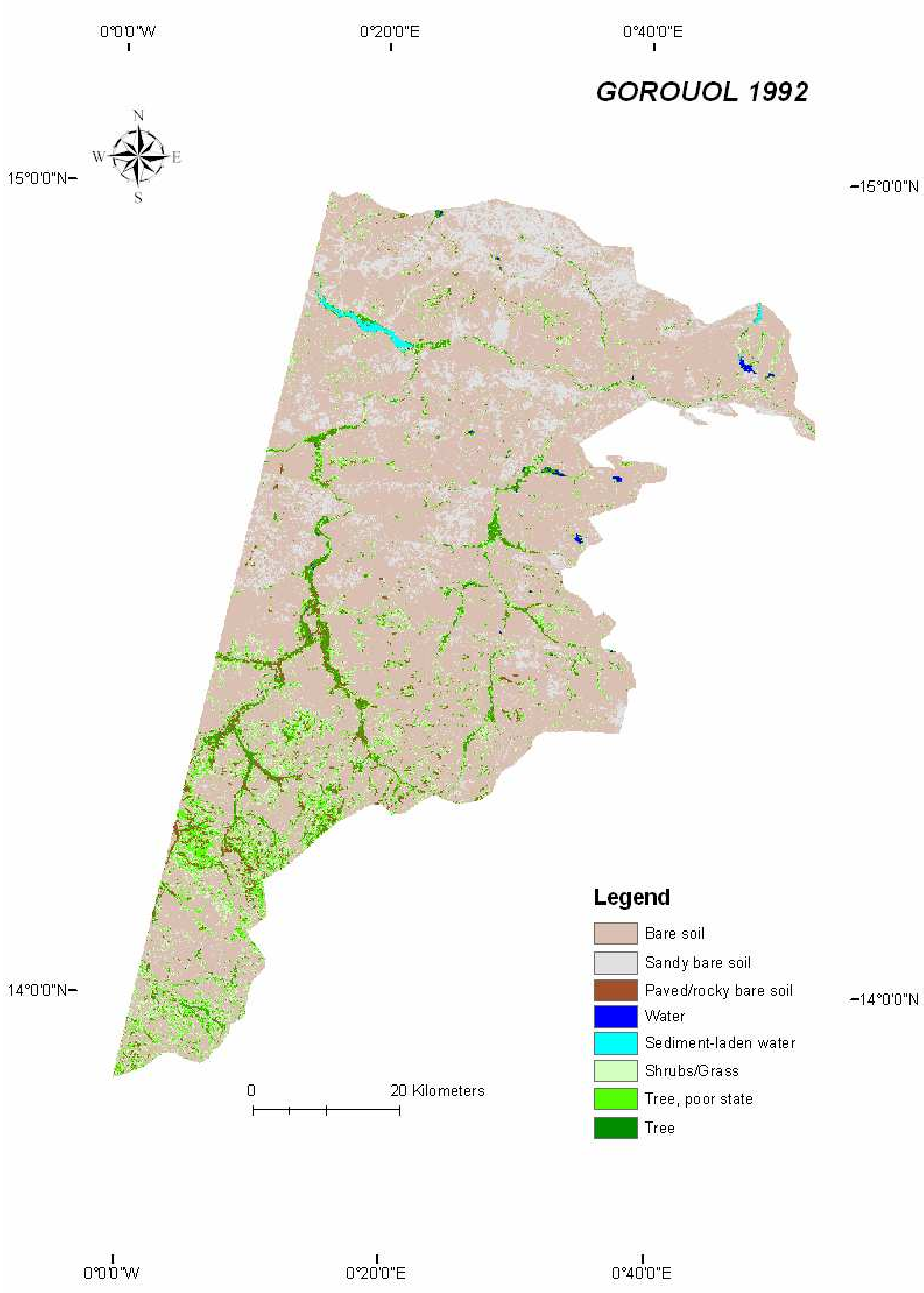


Figure III- 23: Gorouol basin land cover. 18/10/1992 (4757 km²)

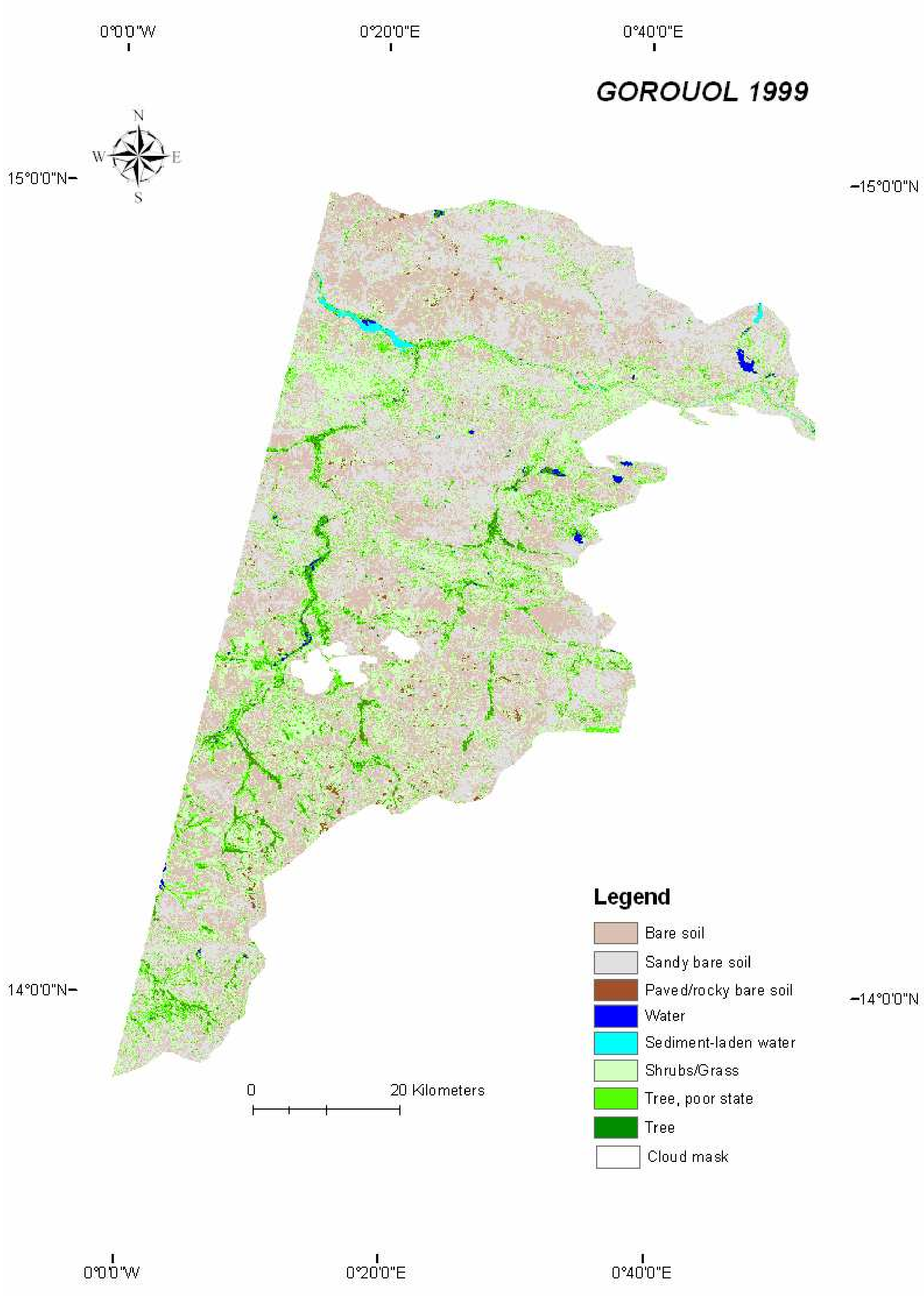


Figure III- 24: Gorouol basin land cover. 22/10/1999 (4757 km²)

Comparisons of the percentage land cover of the area shown in Figure III- 21 to Figure III- 24 . The results of the land cover classification are presented in Table III- 6 and as histograms in appendix C (see Figure C- 2 and Figure C- 3).

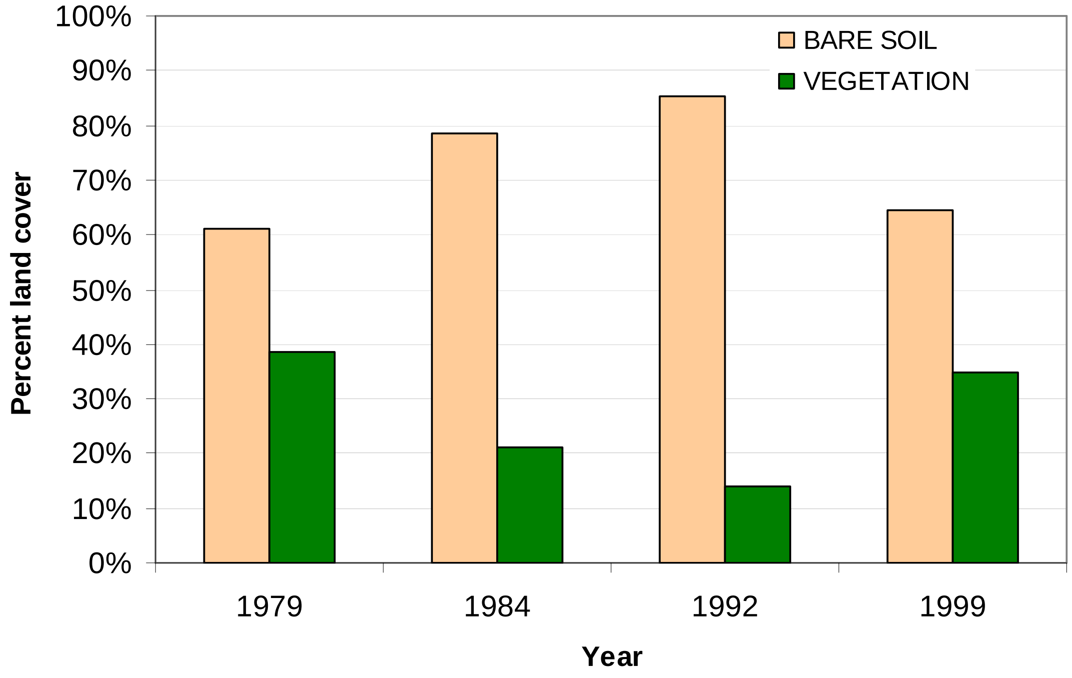


Figure III- 25: Bare and vegetated surface dynamics in the Gorouol Basin (1979 to 1999)

The percentage of bare soil in the Gorouol basin increased from 1979 to 1992: 61% in 1979, 78% in 1984 and 86% in 1992. There was a reduction in bare soil surfaces between 1992 and 1999 from 86% to 65%.

Precipitation decreased between 1979 and 1984 (discussed in part IV) causing a reduction in vegetation cover and increase in bare soil surfaces between the two dates. The relatively significant (for the Sahel) difference in image dates between the 1979 image and the 1992/1999 images make it difficult to compare them directly. A comparison of the 1992 and 1999 images that were acquired at almost the same day of the year indicate an increase in the Shrubs/Grass class (see Table III- 6) from 7% in 1992 to more than 20% in 1999 and to a lesser extent to the tree (poor state) class. Although the total percentage of all bare soil surfaces decreased between 1992 and 1999, the percentage of bare sandy soils, increased in the same period (see Table III- 6), which could have an effect on sediment transfer to the water courses of the sub-basin and to the middle Niger River. The bare sandy soils are a source of sediment that can easily be eroded by wind or water action.

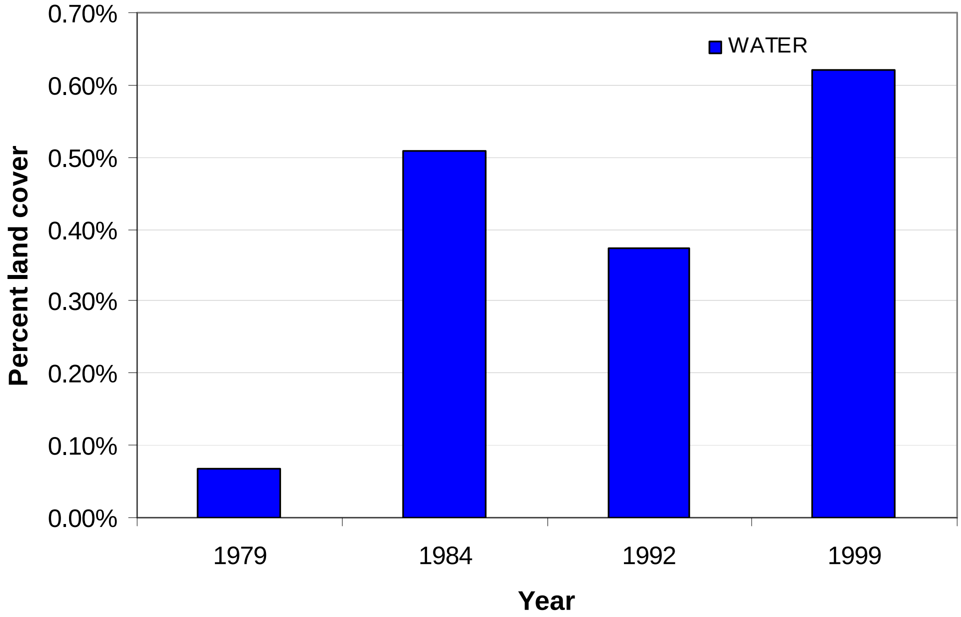


Figure III- 26: Water surface area in the Gorouol basin (1979-1999)

The sharp increase in the water class from 1979 could be due to a number of factors. The 1979 image was acquired on November 29 (later into the dry season than the other images) while the other images were acquired between October 18 and November 5, this time difference is significant in the study region.

The land cover analysis is summarized in Table III- 6 for the 4757 km² portion of the Gorouol basin considered.

Table III- 6: Estimated Land cover of the Gorouol basin 1979 -1999 Area (4757 km²)

Class	1979	1984	1992	1999
Water	0.07	0.18	0.12	0.31
Sediment-laden water	0	0.33	0.25	0.30
Bare soil	44.75	62.67	72.24	35.65
Bare sandy soil	14.95	14.85	11.34	27.49
Bare paved/rocky soil	1.54	0.85	1.89	0.54
Tree	0.61	2.44	2.70	2.65
Tree (poor state)	20.35	1.20	4.42	6.72
Shrubs/Grass	17.74	17.48	7.04	25.15

A comparison of a larger area (14888 km²) of the 45,125 km² Gorouol basin for the 1984, 1992 and 1999 images (see Figure C- 4 to Figure C- 8 and Table C- 16 in appendix C) revealed the same trend, therefore the summary presented can be assumed to be representative of the Gorouol basin for the period.

3.2.2. Change in the Sirba basin between 1975 and 1999 (Area: 1105 km²)

The area common to all the available images (1975, 1984, 1989, and 1999) was only 1105 km² due to the reasons described in paragraph 2. .

The classification results of the Sirba basin for the four dates are presented in Figure III- 27 to Figure III- 30.

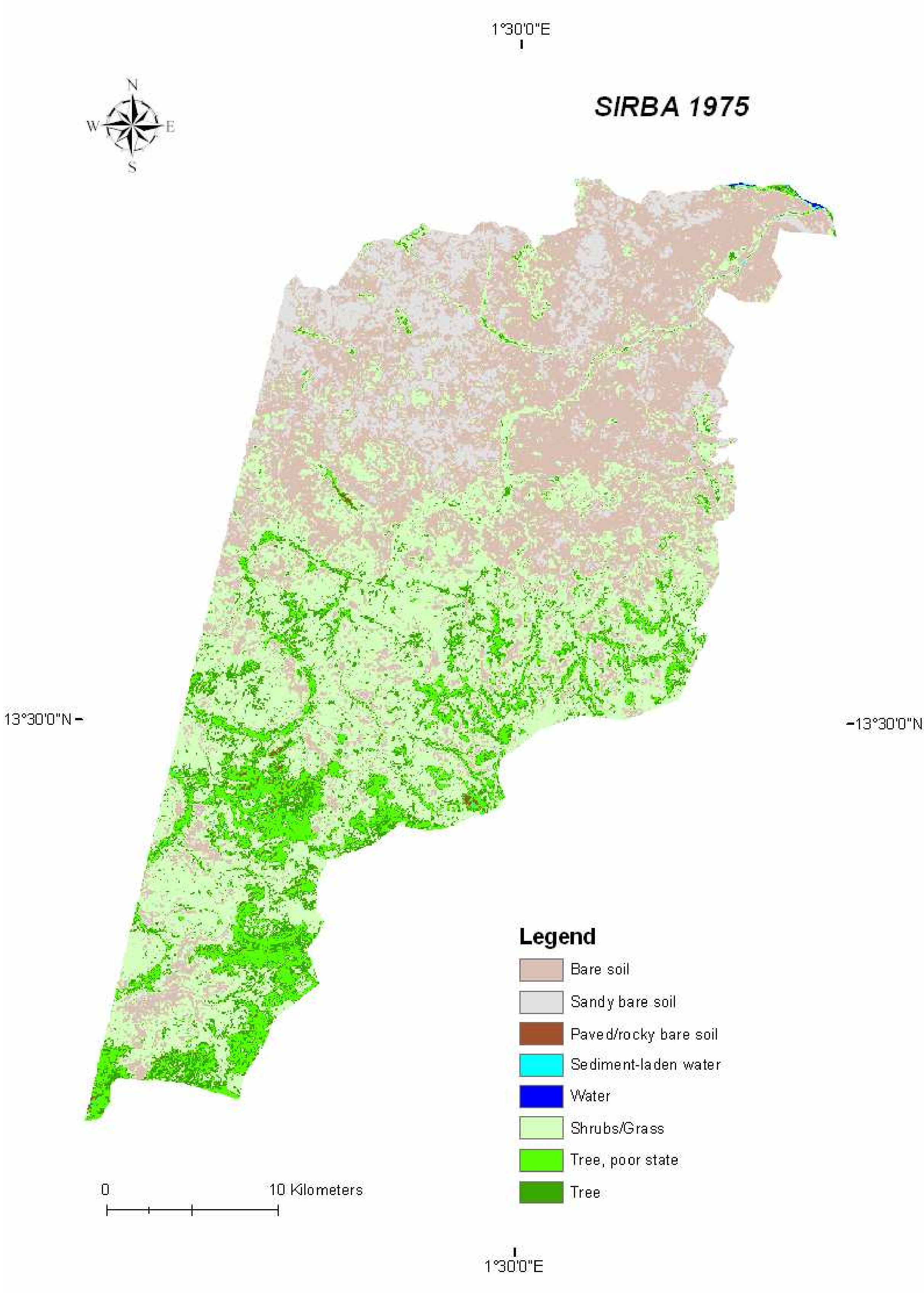


Figure III- 27: Sirba basin land cover.22/11/1975 (1105 km²)

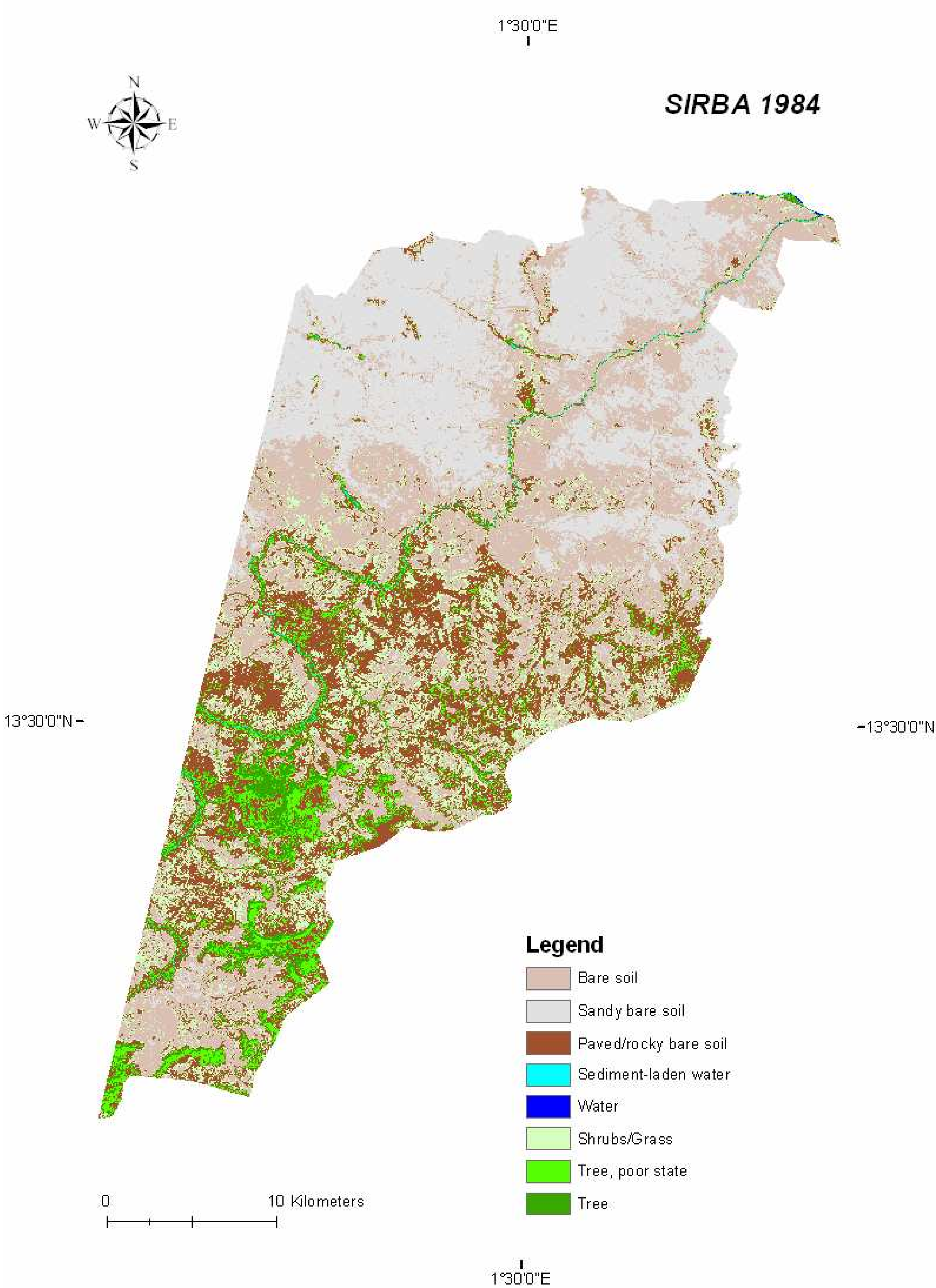


Figure III- 28: Sirba basin land cover.14/11/1984 (1105 km²)

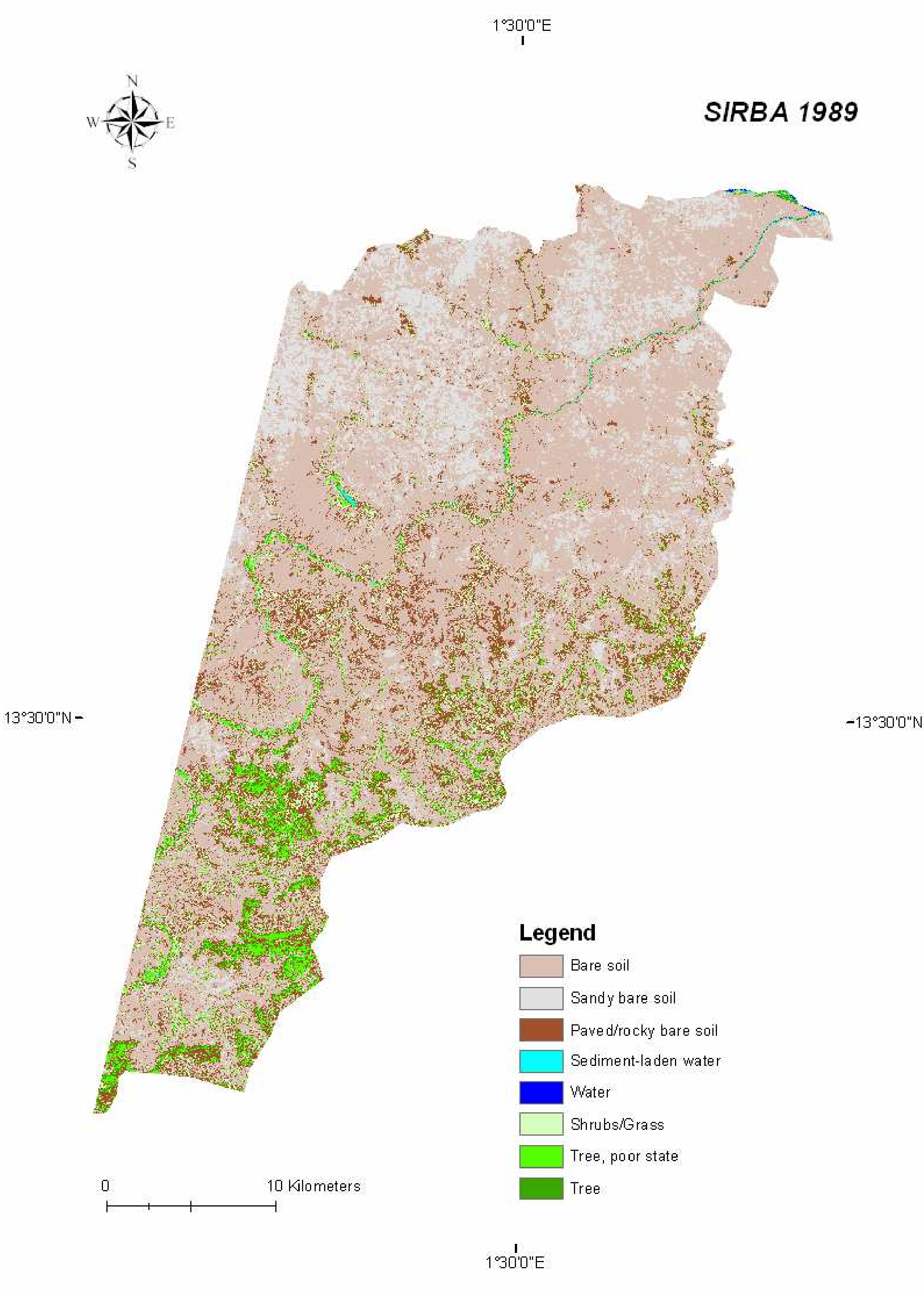


Figure III- 29: Sirba basin land cover.20/11/1989 (1105 km²)

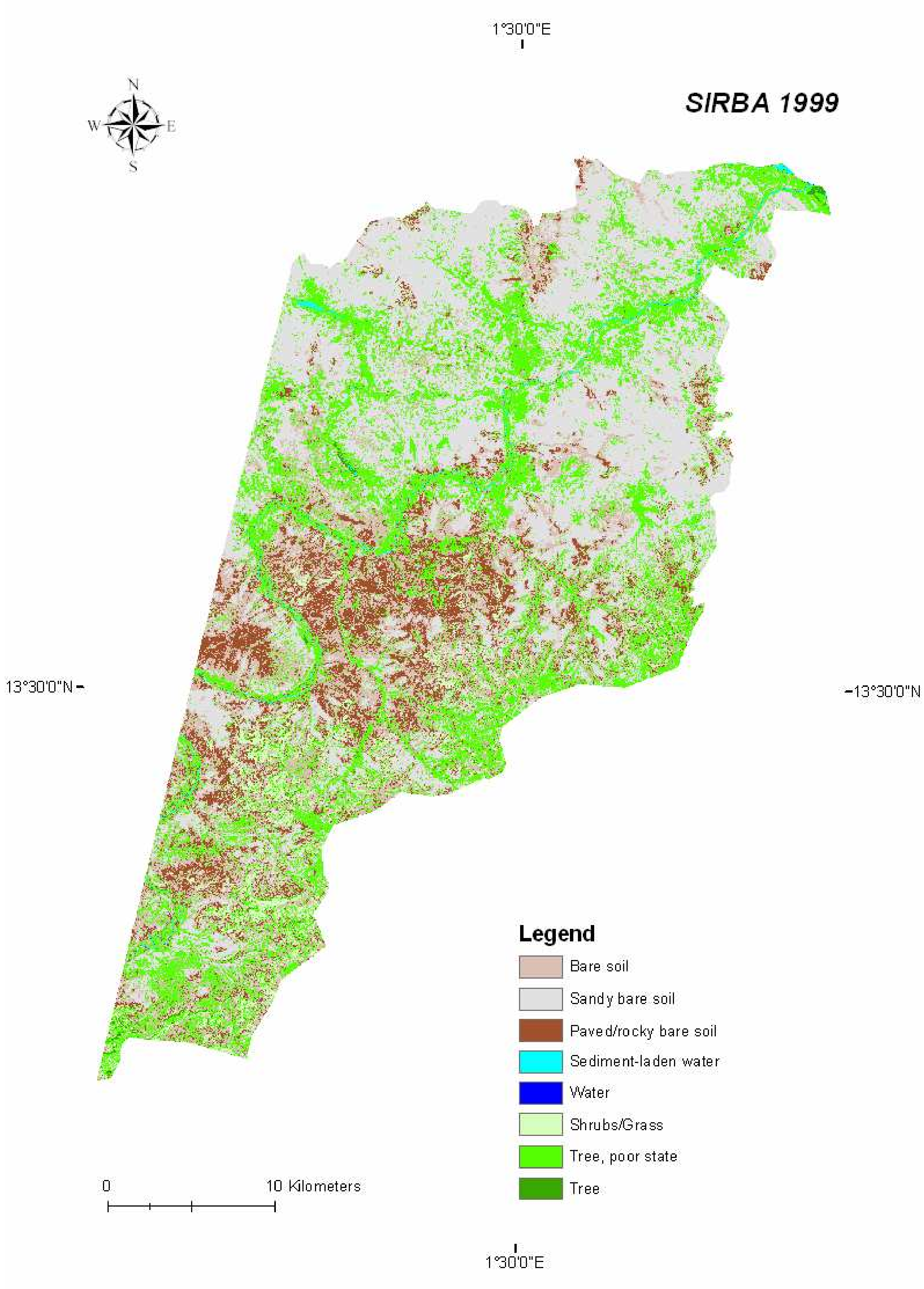


Figure III- 30: Sirba basin land cover.31/10/1999 (1105 km²)

The land cover classifications for the Sirba basin between 1975 and 1999 are presented as percentage bare soil, vegetation, and water surfaces in Figure III- 31 and Figure III- 32.

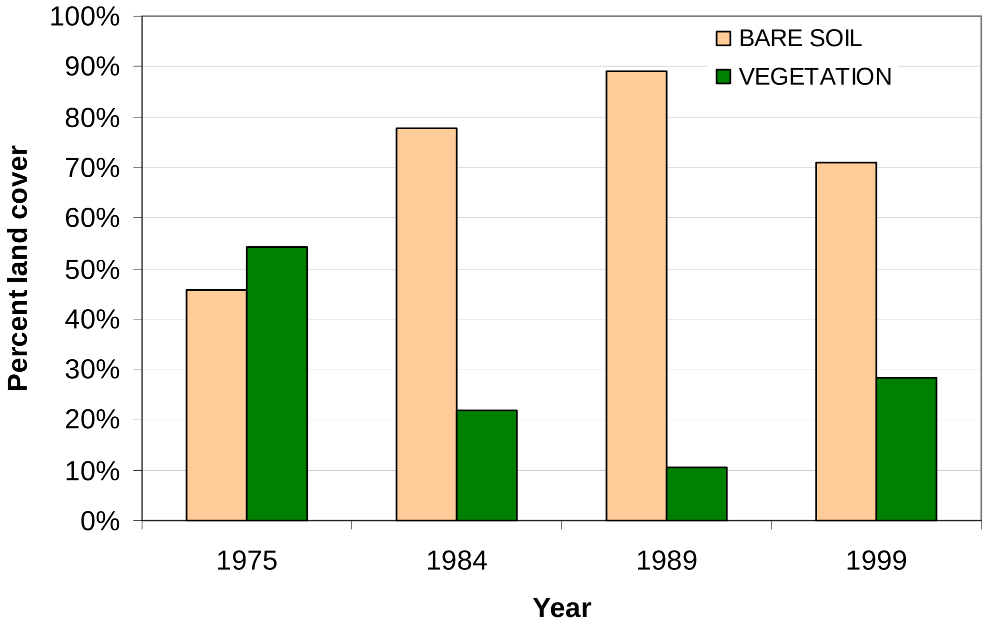


Figure III- 31: Bare and vegetated surface dynamics in the Sirba Basin (1975 to 1999)

As observed in the Gorouol basin where the percentage of bare soil surfaces increased between 1979 and 1992, the percentage of bare soil surfaces in the Sirba basin increased rapidly between 1975 and 1989: 45% in 1975, 78% in 1984 and 89% in 1989. The percentage of bare soil surfaces decreased between 1989 and 1999 from 89% to 71%.

For the Sirba basin, an increase in the percentage of vegetation in the "tree poor-state" class was the cause of the reduction in the percentage of bare soil surfaces.

Between 1984 and 1989, bare soil surfaces increased although 1984 was a particularly dry year compared to 1989. This observation could be due to more intensive vegetation removal between 1984 and 1989. Climatic factors or seasonal effects may not be responsible for this reduction in vegetation cover considering higher precipitation in 1989 and that the images were acquired at almost the same time of the season for both images.

In the Sirba basin, the shrubs/grass class consistently decreased between 1975 and 1999 (see Table III- 7). This class of natural vegetation may have been removed by livestock grazing, or for firewood, and may have given way to cultivated crops (essentially millet) which would have been harvested by the time of acquisition of the images analysed in October or November.

The percentage of bare sandy soil, increased between 1975 and 1999. The bare sandy soil class represents sandy deposits and highly disturbed soils that are easily transported by water or wind.

The percentage of the basin area covered by clear water reduced sharply between 1975 and 1984 (see Table III- 7) apparently due to the severe drought around 1984. Unlike the Gorouol basin where pool and pond formation took place following vegetation removal, the part of the Sirba basin analysed did not follow this trend. Between 1984 and 1989, the area of water in the Sirba basin increased insignificantly from 0.19 km² to 0.26 km² (approximately 0.02% in Table III- 7). The water surface area increased further between 1989 and 1999.

Sediment-laden water mostly in the Sirba River and near its confluence with the Niger River has increased since 1975. There were two periods of increase in sediment-laden water: 1975-1984 and 1989-1999 (see Table III- 7). Between 1984 and 1989 there was a decrease in the sediment-laden water class which occurred at the same time as a reduction in the bare sandy-soil class, which may indicate that a reduction in the supply of easily detachable sediment occurred in this period.

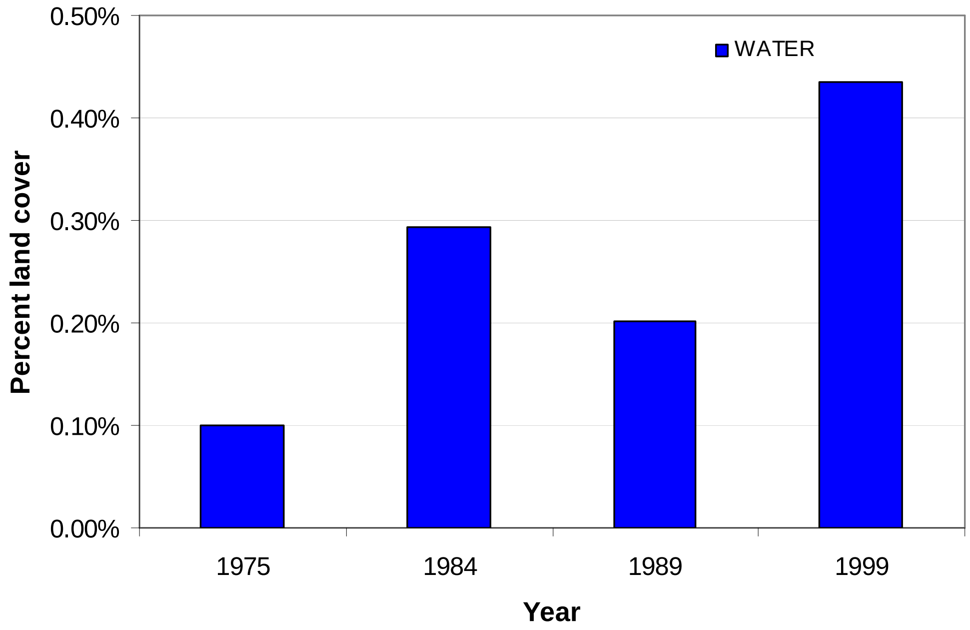


Figure III- 32: Water surface area in the Sirba basin (1975-1999)

Table III- 7: Estimated Land cover of the Sirba basin 1975 -1999 Area (1105 km²)

Class	1975	1984	1989	1999
Water	0.03	0.02	0.02	0.03
Sediment-laden water	0.07	0.28	0.18	0.41
Bare soil	34.75	32.55	60.56	21.93
Bare sandy soil	10.74	25.44	14.83	38.59
Bare paved/rocky soil	0.27	19.93	13.68	10.64
Tree	7.75	2.77	0.89	0.34
Tree (poor state)	7.13	5.04	3.86	24.48
Shrubs/Grass	39.26	13.98	5.98	3.62

The results of the land cover comparison of a larger area of the Sirba basin (5104 km²) between 1984 and 1999 are presented as histograms in Figure C- 11 to Figure C- 13 and summarized in Table C- 17 in appendix C. The land cover results on this larger area confirm the results obtained in the comparison of the 1975, 1984, 1989 and 1999 images for a smaller area of the basin.

A comparison of a larger area (5104 km²) of the 38,750-km² Sirba basin for the 1984, 1989 and 1999 images (see Figure C- 11 to Figure C- 15 and Table C- 17 in appendix C) revealed the same trend; therefore the summary presented can be considered representative of the Sirba basin for the period

3.2.3. Change in the Mékrou basin between 1973 and 2000 (Area: 7690 km²)

For the Mékrou basin, only two dates are compared: 1973 and 2000 with an area of 7690 km² common to both images, because the images for 1973 did not cover the entire basin. The images that were compared for the Mékrou basin are presented in Figure III- 33 (for 1973) and Figure III- 34 (for 2000).

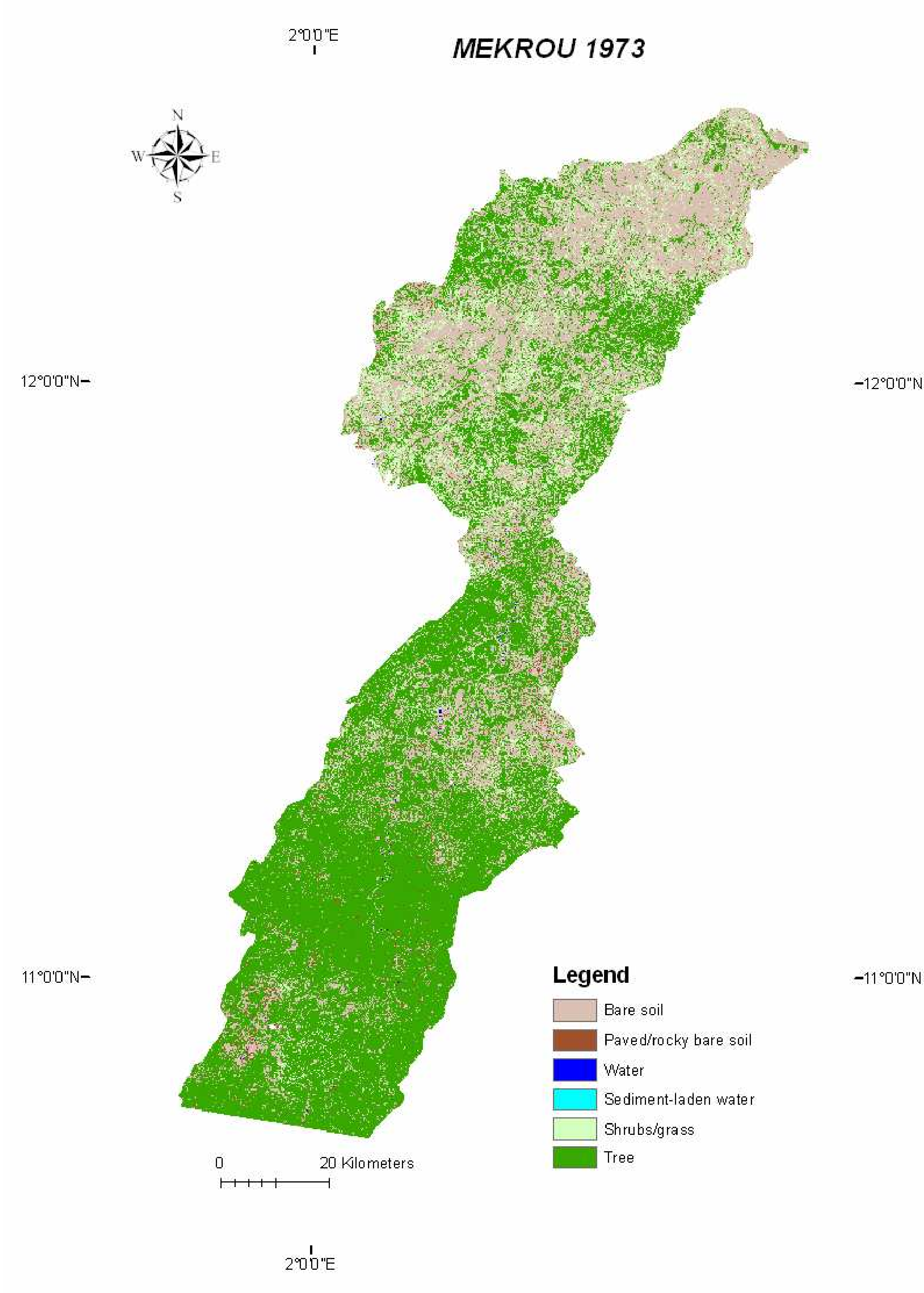


Figure III- 33: Mékrou basin land cover.17&18/10/1973 (7690 km²)

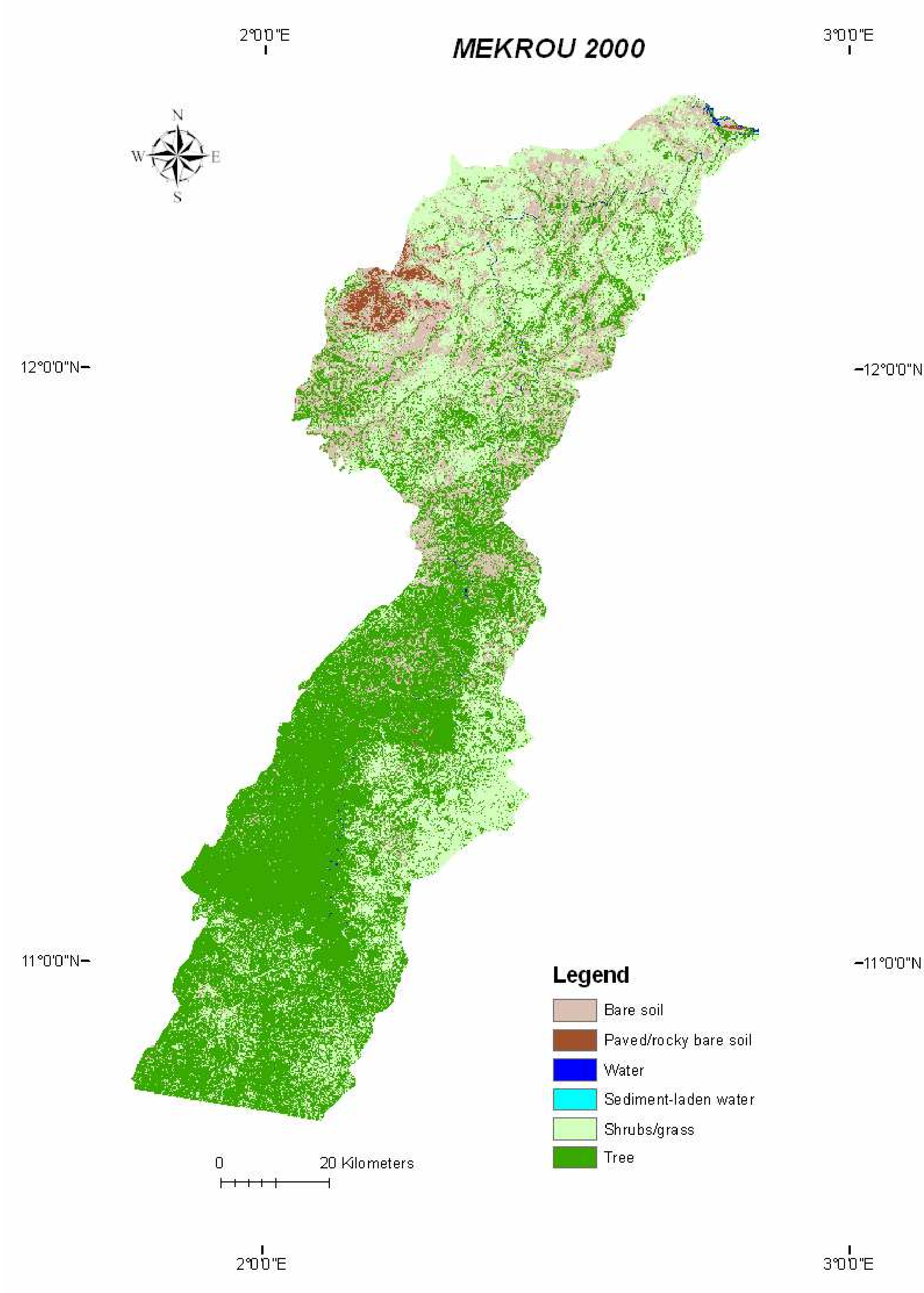


Figure III- 34: Mékrou basin land cover.26/10/2000 (7690 km²)

From the results of the land cover classifications for the Mékrou basin for 1973 and 2000 a comparison of the bare soil, vegetation and water classes is presented in Figure III- 35 and Figure III- 36.

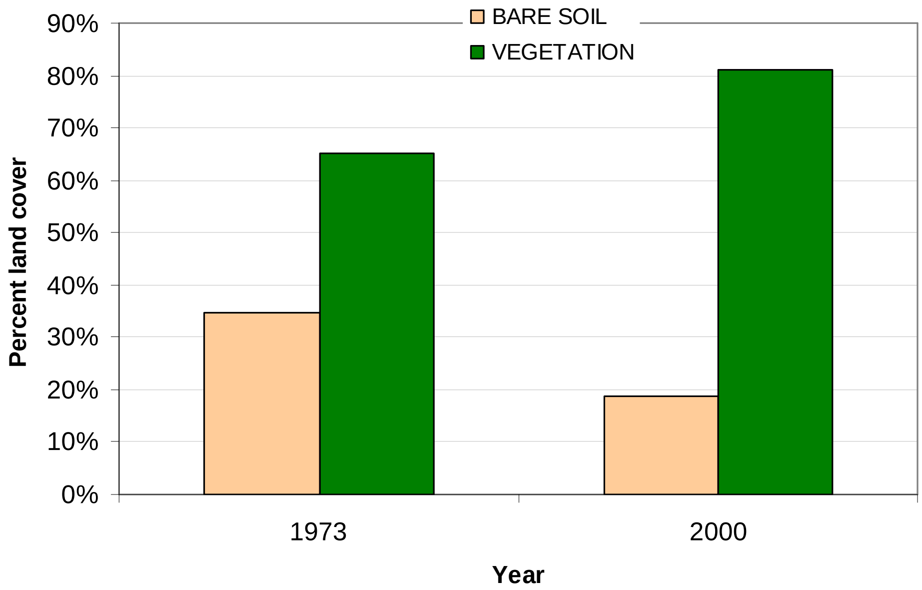


Figure III- 35: Bare and vegetated surface dynamics in the Mékrou Basin (1973 to 2000)

Contrary to the trend of increasing bare soil surfaces in the two Sahelian basins (the Gorouol and The Sirba), the percentage of bare soil surfaces in the Mékrou basin reduced between 1973 and 2000 from 35% to 19%. The increase in vegetation cover observed in the Mékrou basin was as in the Gorouol basin a result of an increase in the Shrubs/Grass class. The Shrub/Grass class did not only replace some of the bare soil surfaces but also replaced some of the pixels in the "tree" class which reduced from 54% to 48% between 1973 and 2000 (see Table III- 8). The principal reason for the increase in vegetation cover in the Mékrou basin between 1973 and 2000 is the success of the Parc Regional –W (established in the 1960s) located in this area to proctect flora and fauna.

The percentage of clear surface water increased in the Mékrou basin between 1973 and 2000.

A comparison of the percentage land cover of the area shown in Figure III- 33 and Figure III- 34 is presented in Table III- 8 and as histograms in Figure C- 16 and Figure C- 17 (in appendix C).

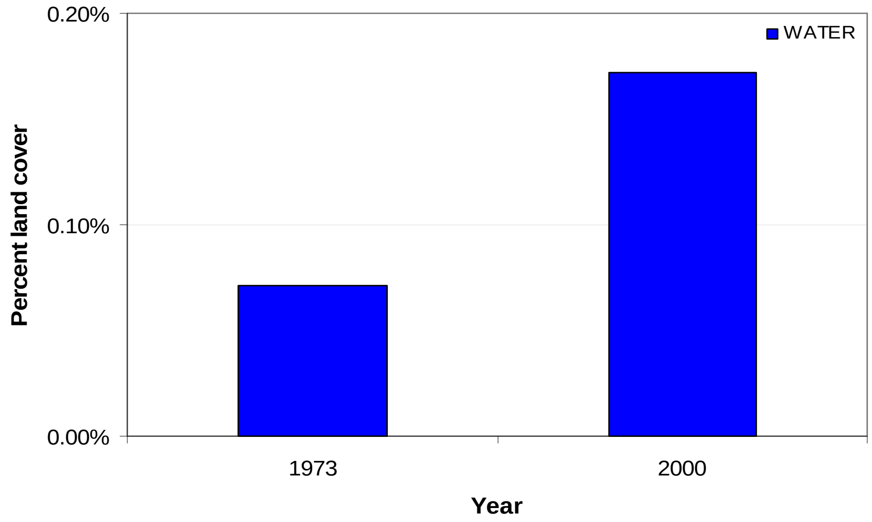


Figure III- 36: Water surface area in the Mékrou basin (1973-2000)

Table III- 8: Estimated Land cover of the Mékrou basin 1973 -2000 (7690 km²)

Class	1973	2000
Water	0.07	0.17
Sediment-laden water	0	0
Bare soil	33.55	17.56
Bare paved/rocky soil	1.16	1.03
Tree	54.27	48.21
Shrubs/Grass	10.94	33.02

3.2.4. Summary

In summary, the analysis of land cover change indicates that the study area has been undergoing constant change since the 1970s. A trend of increasing bare soil surfaces was observed for the two Sahelian basins: the Gorouol (1979 to 1992) and the Sirba (1975 to 1989). in the Gorouol basin an increase of water surfaces was due to an increase in small dams and water reservoirs, a similar situation of increasing water retention by dams in the region was reported by Mahé et al. [2005] for the Nakambe basin in Burkina-Faso. In the Sirba basin, the increase in water surface area occurred due to flowing water, essentially the Sirba River and its tributaries.

For the two Sahelian basins, a slight increase in vegetation cover was observed between 1992 and 1999 for the Gorouol basin, and between 1989 and 1999 for the Sirba basin. Again, the causes were different in both basins. An increase in Shrubs/Grass occurred in the Gorouol while in the Sirba there was a slight increase in wooded vegetation.

In the ~120,000 km² upper Niger River basin, Ruelland et al. [2008] observed a moderate deforestation and land clearance tendency between 1975 and 2000. Similar trends of vegetation reduction have been reported on smaller areas in Sahelian Niger. Leblanc et al. [2008] studied the vegetation cover of a 137 km² basin 60 km north-east of Niamey between 1950 and 1992 and reported percentage wooded vegetation cover of 65% in 1950, 47% in 1975 and 27% in 1992, illustrating the consistent reduction in vegetation cover between 1950 and 1992. More recent vegetation studies argue for a "greening" of the Sahel [*A Anyamba and C J Tucker*, 2005; *S Nicholson*, 2005] as above average NDVI conditions were observed between 1994 and 2003. However, while the precipitation levels seem to approach pre-drought levels, opinion is divided over the reported greening of the Sahel. Hountondji et al. [2004] observed increasing precipitation in 98% of 109 rain gauge stations located in the Sahelian part of the republic of Niger.

Considering the rain use efficiency (RUE) which is the ratio of annual net primary production and annual rainfall, other authors have found a weakness in the use of NDVI as the sole means of evaluating vegetation degradation. According to Hein and DeRidder [2006], a decline in RUE over time indicates ecosystem degradation because it reflects a reduced capacity of the vegetation to transform water and nutrients into biomass. Hein and Deridder posited that in the absence of human-induced degradation the upward trend in rainfall should have caused an increase in RUE. By measuring phytomass production over time, Hein and DeRidder [2006] showed that RUE had remained stable despite the increasing rainfall in recent times while Hountondji et al. [2004] observed a widespread reduction in RUE.

In some Sahelian areas that have experienced some regeneration of vegetation cover evidence showing that the species composition of the regenerating vegetation had changed since the drought of the 1970s [*K Rasmussen and B Fog, .Madsen,J.E.*, 2001].

The more densely vegetated Mékrou basin did not experience significant vegetation removal as observed in the two Sahelian basins. Although there was a slight decrease in the percentage of trees, bare soils surfaces did not increase. Shrubs and grass replaced the trees and bare soil surfaces.

An understanding of the land cover changes in the study area will be useful in assessing the possible impacts on sediment production and transport. Vanacker et al. [2005] noted the significance of changes in spatial organisation and connectivity of land use systems on river sediment transport even with relatively small land use and land cover changes.

4. Conclusions

One of the working hypotheses of this study was that the sharp decrease in vegetation cover due to climatic and human impacts in the Sahel was causing an increase in the availability of sediment in Sahelian rivers.

- The study has shown that there was an intense decline in the vegetation cover of the Gorouol and Sirba basins between 1970 and 1989/1992. Sediment availability particularly in the Sahelian basins can be expected to be on the increase considering the increase in sandy bare soils between 1992 and 1999 for the Gorouol basin and between 1975 and 1999 for the Sirba basin.
- A reduction of bare soil surfaces was observed in the two Sahelian basins between 1992 and 1999 for the Gorouol basin, and between 1989 and 1999 for the Sirba basin. An increase in the Shrubs/Grass class was the main cause of an increase in total vegetation cover in the Gorouol basin. The increase in the Tree poor state class was the main reason for an increase in total vegetation of the Sirba basin between 1989 and 1999, although the difference in image dates may have biased the observation.
- In contrast, the Sudanian Mékrou basin while also changing was affected to a lesser extent by vegetation removal between 1973 and 2000, due to the effects of the Parc W conservation that extends into the Mékrou basin.
- In addition to the use of Landsat imagery of varying spatial and spectral resolutions, the study has shown that when available Corona images can be applied to improve the amount of remotely sensed information for land cover analyses in the Sahel. While the application of Corona imagery may require a high amount of computer processing space and may require a lot of processing time, they can provide invaluable information in Sahelian areas without an excessive amount of deformation considering that the terrain is relatively smooth.

Part IV-Elements of hydrology and discharge measurements

1. Is the Niger River under threat?

River basins are an important part of natural ecosystems that provide a means of livelihood for its human inhabitants particularly in developing countries. The need to harness river resources for various human uses often endangers the population that depend on it for their livelihoods as well as the balance of the flora and fauna that are found in it.

In the Niger River basin, with increasing population growth, human activities such as water extraction, navigation, damming, discharge of industrial and domestic effluent, and over fishing will pose a threat to the well-being of the basin if not properly managed.

Climate change or variability, with its effects on precipitation, evaporation, and river discharge in the Niger River basin and in particular, the semi-arid middle Niger basin further complicates the sustainable management of the river basin.

A combination of climate change and the growing human impacts on the river's resources have seen the Niger River dry up at Niamey on a couple of occasions in the last few decades. This pressure may make the routine task of sediment regulation more difficult even for a large river like the Niger. It is not the purpose of this part of the study to make a complete hydrological analysis of the study area, but to review and analyse some of the elements that are linked to sediment production and transfer in the study area that will be discussed in part V of this work. Specific attention to the hydrology of the region can be found in Brunet-Moret et al. [1986] and more recently in Amani and Nguetora [2002] and in Mahé et al. [2003, 2005] amongst others.

This part of the study aims to explore the Niger River basin in the larger context of large African rivers and to attempt to describe the effects of environmental change on the middle Niger River's discharge.

In order to achieve the stated objective, it would be necessary to:

- Characterise the discharge regime of the middle Niger River in relation to:
    - the Niger's regime upstream of the study area;
    - the effect of climatic variability and a reduction in precipitation.
- Characterise the discharge of the Niger River at Niamey during the study period with respect to the long-term average.

It was also necessary to simulate discharge values where no direct measurements were made in order to provide data for the sediment studies in part V of this study.

1.1. Flood regimes:

A river's regime is its expected pattern of flow during a hydrological year [*E M Shaw*, 1994], and is usually derived from flow records of 20 to 30 years. River regimes are controlled by climatic factors, such as precipitation and evaporation as well as the river basin's characteristics such as soil type, vegetation cover, slope, basin size etc.

1.1.1. Major African rivers

The marked wet and dry seasons in tropical Africa result in a close linkage between the climatic conditions of these river basins and their river regimes.

The meteorological and corresponding hydrological classifications in Africa according to Rodier [1964] are presented in Table IV- 1.

Table IV- 1 : Meteorological classification of Tropical Africa and corresponding hydrological regimes

Precipitation (mm)	Meteorological Classification	Hydrological Classification
< 150	Saharian	Desert
150 – 300	Northern Sahel	Sub- desert
300 – 750	Southern Sahel	Sahelian
750 – 1200	Sudan I	Pure Tropical
> 1200	Sudan II and III	Tropical transition
Below 8°& 9°	Libero-Dahomean	Equatorial transition

River basins covering relatively large areas are therefore bound to be influenced by factors such as the varying precipitation of the basin area to seasonal differences within the basin. The regimes of such rivers may vary markedly along their lengths in terms of timing and magnitude of discharge. A graphical representation of the above climatic classification for West and Central Africa is presented in Figure IV- 1.

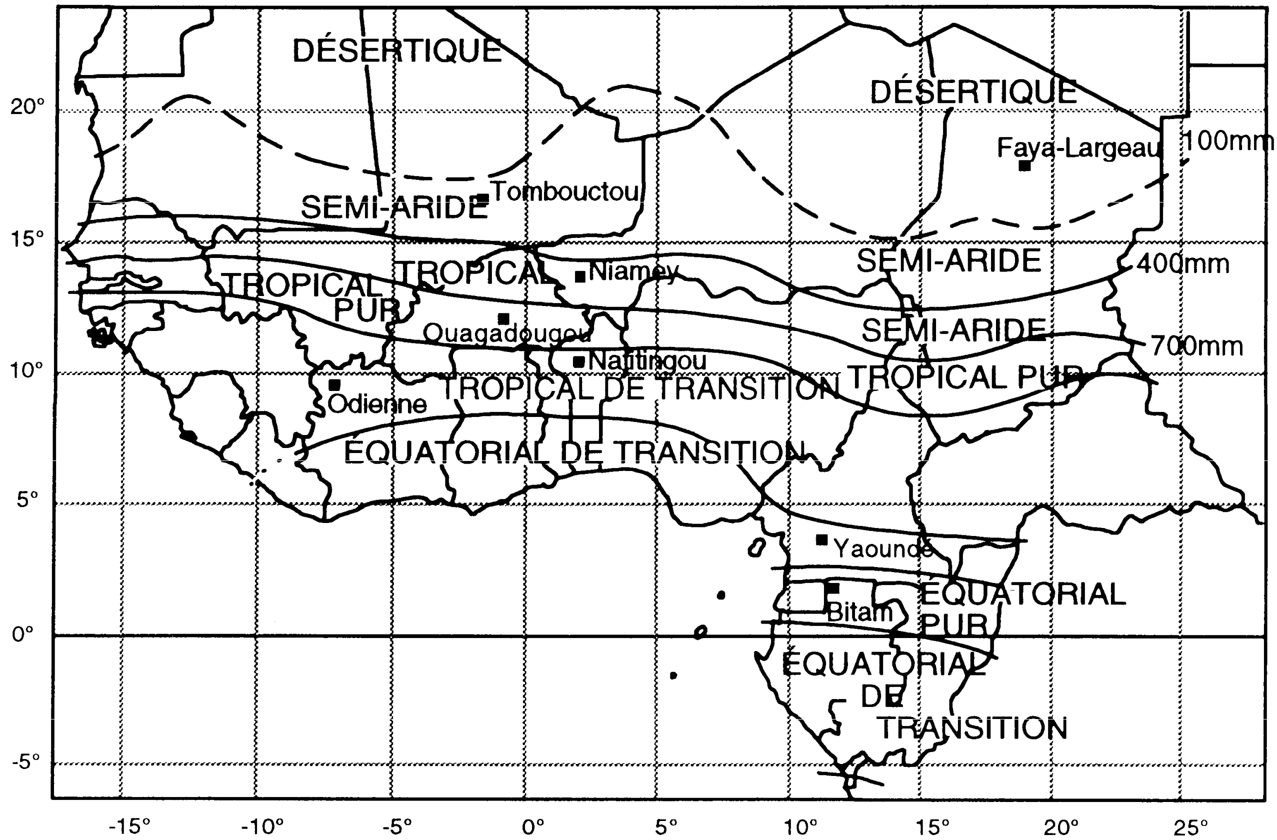


Figure IV- 1: West and central African climates after L'Hôte et al. [1996]

In order to appreciate the peculiarities of the middle Niger River's regime, a brief description of the regimes of two other large African rivers near their mouths is presented.

- **The Nile**: The Nile river basin covers an area of about 3.08×10^6 km² [*UNEP*, 2002] and the river flows for about 6700 km before reaching the Mediterranean sea. The Nile River has three major tributaries, namely, the White Nile, the Blue Nile, and the Atbara, with two distinct regimes, the White Nile on one hand and the Blue Nile and Atbara on the other hand. The White Nile maintains a relatively constant flow all year through due to storage in lakes and evaporation losses as it traverses the Sudd, a vast, flat expanse of swamps. The Blue Nile and Atbara are seasonal rivers that are largely influenced by the wet and dry season of the tropical regime, flooding in the wet season due to heavy rainfall on the Ethiopian plateau and receding in the dry season. A characteristic hydrograph of the Nile at Aswan (3.06×10^6 km²) is presented in Figure IV- 2 showing the near constant flow due to the White Nile and the peak flow due to the Blue Nile and the Atbara. The Nile has a relatively low specific discharge (0.9 l/s/km²) due to a large part of its basin being located in arid areas.

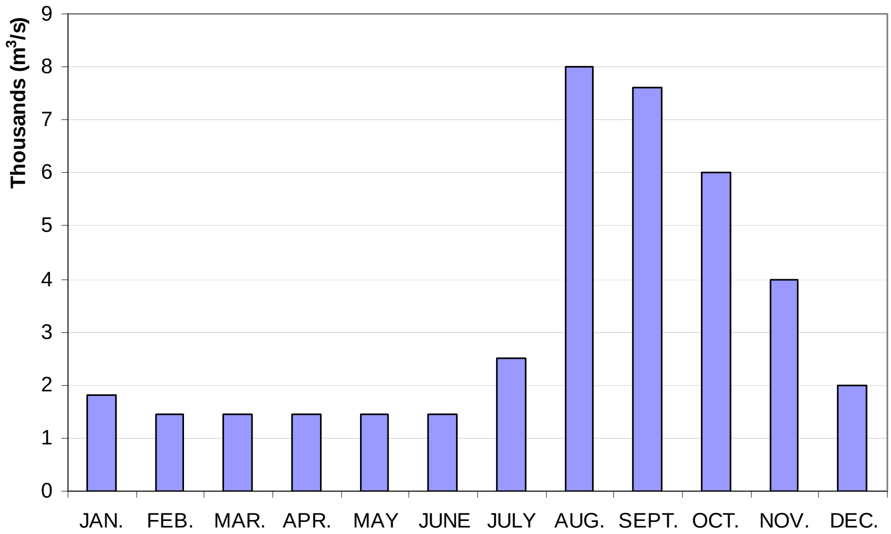


Figure IV- 2: Characteristic hydrograph of the Nile River at Aswan after Mohamed et al [2005]

- **The Congo**: The Congo river is 4700 km long [*J C Olivry et al.*, 1988] and has a basin area of about 3.7×10^6 km² which is located on north and south of the equator. The volume of water discharged annually by the Congo is one of the world's highest, with a high specific discharge of 11.7 l/s/km². The main controlling factor of the Congo River's regime is its location on either side of the equator causing an alternation in the rainy season on either side of the equator. The Congo River basin has two periods of peak flow (see Figure IV- 3) for the station at Brazzaville ($\sim3.5\times10^6$ km²): the more significant flood period occurs between October and January and is due to the contribution from the northern part of the basin. The lesser flood period occurs between April and May and is due to contribution from the southern part of the basin. Laraque et al.[2001] discuss the variations in hydrological regime of the Congo River.

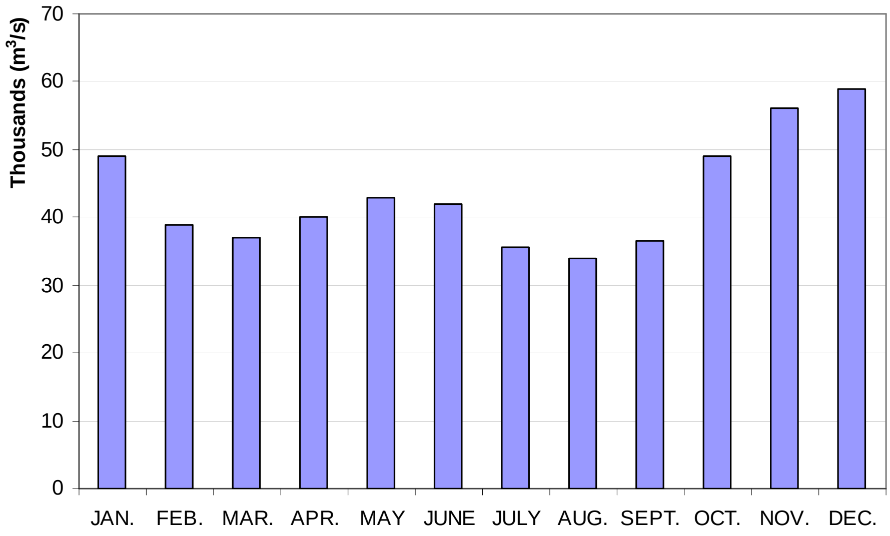


Figure IV- 3: Characteristic hydrograph of the Congo River at Brazzaville after Bricquet [1993]

There are also two periods of low flow with the more severe low flow period occurring between June and September due to low flows of the equatorial regime and the falling limb of the southern tropical regime; and a second low flow period between February and March due to the low flows of basin areas located in the northern hemisphere.

A comparison of these two major African river basins with the Niger basin at Niamey and at Onitsha is presented in Table IV- 2, with Nile river data from [*Y A Mohamed et al.*, 2005] and Congo river data from [*J P Bricquet*, 1993; *J C Olivry et al.*, 1988].

Table IV- 2: Flow characteristics of the major African rivers

River (station)	Area (10^6 km²)	Modal discharge (10^3 m³/s)	Specific discharge (l/s/km²)	Mean annual discharge volume (10^9 m³)
Nile (Aswan)	3.06	2.7	0.9	84.1
Congo(Brazzaville)	3.50	40.9	11.7	1290.0
Niger(Onitsha)	1.47*	5.9	4.0	200.0
Niger(Niamey)	0.70*	1.0	1.4	31.0

** considering an active basin area of (*1.5×10^6 *km²)*

1.1.2. The Niger River from its source to Malanville

The varying climatic regions traversed by the Niger River as well as it large catchment basin give it a variable regime along its length from its source to its mouth.

The climatic regions that affect the Niger River's hydrological regime from North to South according to Rodier [1964] are the following (see Table IV- 1):

1) **The northern Sahel**: The sub-desert flow regime occurs in regions between the 100mm and 300mm isohyets or the northern Sahel. The sub-desert hydrologic regime is marked by infrequent runoff during the short rainy season and a high degree of evaporation.

2) **The southern Sahel**: The Sahelian regime prevails between the 300mm and 750mm isohyets. The rainy season in the southern Sahel lasts for about three months, starting in May/June and ending in September/October. Sahelian watercourses attain their peak flow around August and are dry or maintain a very low base flow between November and the next rainy season.

3) **Sudan I**: The pure tropical regime has a season of high flows between July and October, and a low flow season between December and June. The northern limit is the 750mm isohyet and the southern limit is the 1200mm isohyet.

4) **Sudan II and III**: Rivers in the Sudan II and III climatic region, with a longer rainy season than the Sudan I region, have a tropical transition regime marked by a longer period of high river discharge and less severe low flows than the Sahelian and Sudan I regimes.

The Niger's discharge increases steadily from its source through its upper course until the inner delta where it losses about 24 to 48% of its volume to evaporation and infiltration [*G Mahé et al.*, 2002], depending on the prevailing climatic conditions. Rodier [1964] estimated that between 22.5 and 43 billion m^3 of water are lost per annum due to evaporation and infiltration as the Niger river traverses the flat semi-arid region known as the Niger's interior delta , that attains a maximum surface of about 35000 km^2 according to Mariko et al.[2002].

The characteristics of the Niger River from Kouroussa to Malanville up to 1979 are summarized in Table IV- 3, and the relative locations of the stations are presented in Figure IV- 4. The data are compared only up to 1979 because of issues of data availability for some of the stations.

Table IV- 3: The Niger River from Kouroussa to Malanville

	Upper Niger River		Inner Delta		Middle Niger River	
	Tropical transition regime		*Sahelian*	*Sahelian*	*Sahelian*	*Pure Tropical*
	Kouroussa[1] (1945-78)	**Koulikoro**[1] (1907-79)	**Koulikoro + Bani**[1] (1951-79)	**Diré**[1] (1924-79)	**Niamey**[2] (1929-79)	**Malanville**[2] (1952-79)
Basin area (km²)	16560	120000	236000	340000	700000	1000000
Precipitation(mm)	1650	1600	1405			
Annual Mean discharge(m^3/s)		1545	2050	1110	996	1175
Annual Modal discharge(m^3/s)	238	1505	2070	1090	970	1255
Low flow(m^3/s)	6	46	66	50	41	60
Mean peak discharge(m^3/s)	1127	6139	8320	2350	1840	2204
Median cumulative annual discharge(m^3)	NA	49×10^9	70×10^9	35×10^9	30.9×10^9	40×10^9
Cumulative annual discharge(90th percentile) wet year(m^3)	NA	63.5×10^9	90×10^9	47×10^9	38.5×10^9	50×10^9
Cumulative annual discharge(10th percentile) dry year(m^3)	NA	33.5×10^9	50×10^9	27.5×10^9	21×10^9	29×10^9
10 year Flood(m^3/s)	NA	7900	11080	2660	2135	2197
100 year Flood(m^3/s)	NA	9600	13350	2800	2540	3020

[1] *data from Rodier and Roche[1984] and Brunet-Moret et al.[1986]*; [2] *data from NBA archives*

In Table IV- 3, the first estimation of discharge in the inner delta is derived from the addition of river discharge values of the Niger River at Koulikoro and the Bani River at Douna (K+D) in Figure IV- 4 although the inner delta begins at Ké-Macina.

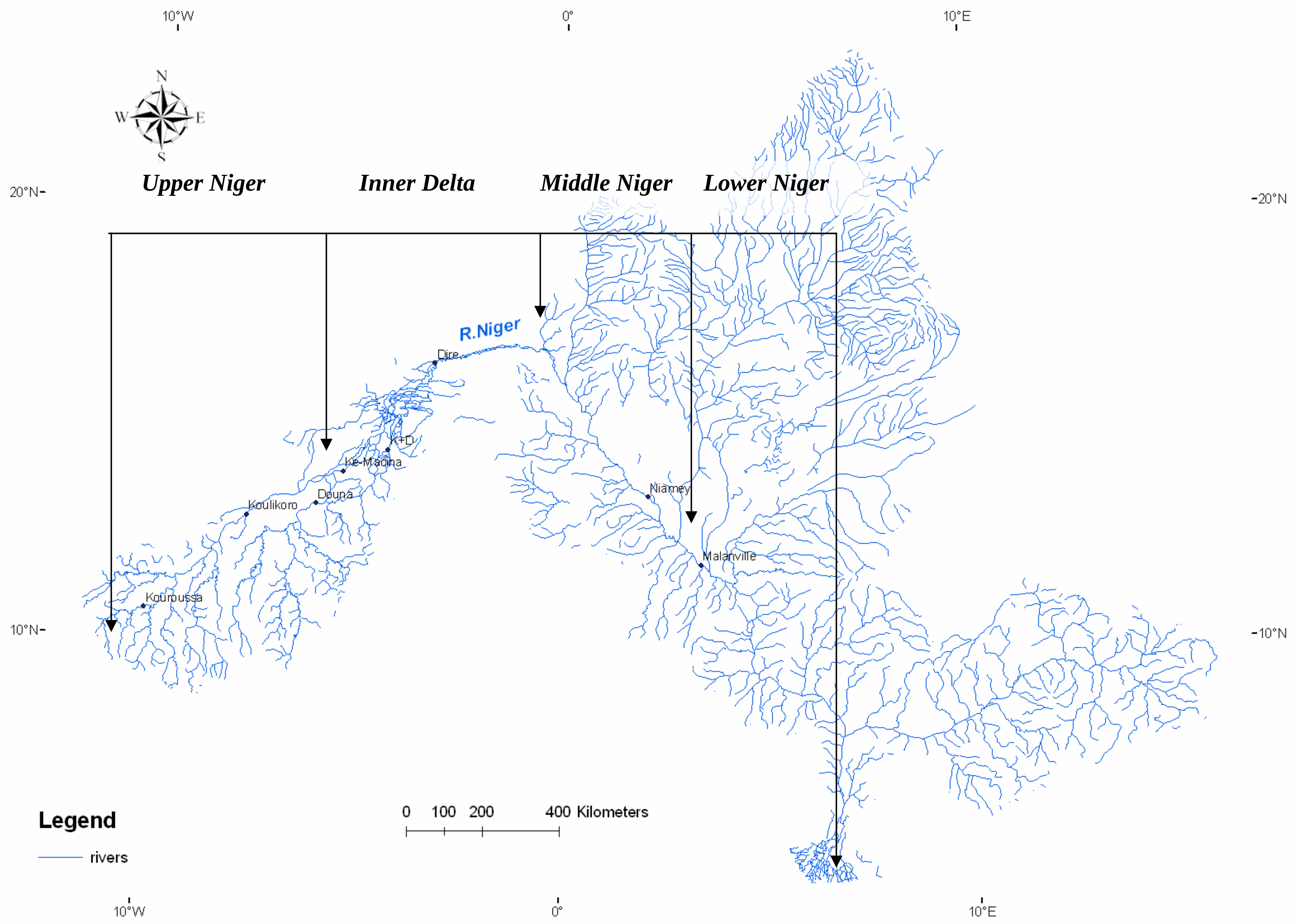


Figure IV- 4: The Niger River from its source to Malanville

Hydrographs for the representative stations along the Niger from Kouroussa to Malanville are presented in Figure IV- 5 using data from the Niger Basin Authority, to illustrate the variability in river discharge along the river for a given hydrological year.

The continuous increase in discharge of the Niger River can be observed from Kouroussa to Koulikoro after which on traversing the inner delta, large evaporation and infiltration losses occur. Further losses occur between Diré and Niamey.

The Niger in 2006/07 at Kouroussa near its source reached its peak discharge around October at less then 800 m^3/s, while at Koulikoro the maximum discharge was about 4000 m^3/s. The discharge at Kouroussa has more than one peak reflecting the contribution of the tributaries near the Niger's source.

The maximum discharges at Kouroussa and Koulikoro on the upper Niger have sharp peaks that are not sustained in comparison to the Niger's hydrograph at Diré at the outlet of the inner delta. The sustained peak observed at Diré is due to the storage that occurs in the Niger's inner delta. The maximum discharge at Diré of about 2000 m^3/s occurred around November.

The middle Niger at Niamey has two distinct peaks, the first one is due to the local rainy season and occurs around August and the second peak is due to the emptying of the inland delta and occurs around December or January. Historically, the second peak discharge that occurs in December or January was much larger than the first peak discharge, but the trend has changed in recent times as will be discussed in the following sections. In 2006/07, the first peak was about 1840 m^3/s while the second peak and more sustained maximum discharge was about 1770 m3/s.

The hydrograph in

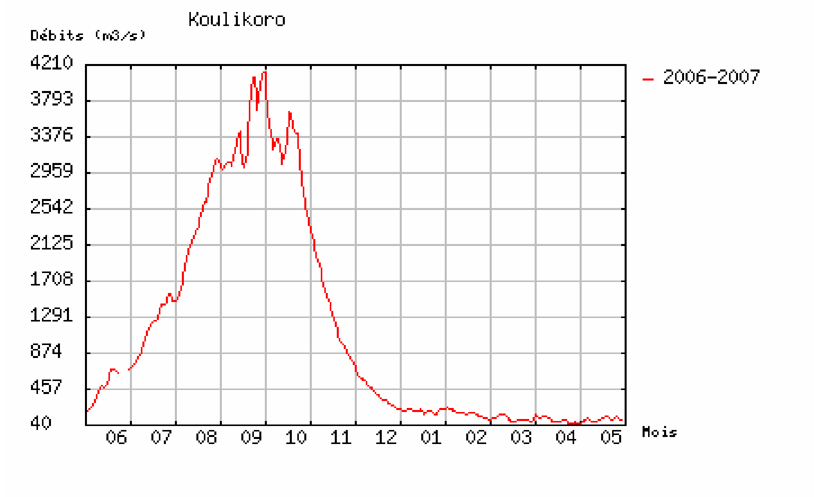
Figure IV- 5(e) for the Niger at Malanville 1989/90 is presented only to illustrate the hydrograph at Malanville with a similar shape to the Niger's hydrograph at Niamey.

An overview of the land use and climatic changes in the Sahel and Sudan areas of West Africa is presented in Descroix et al. [2009]

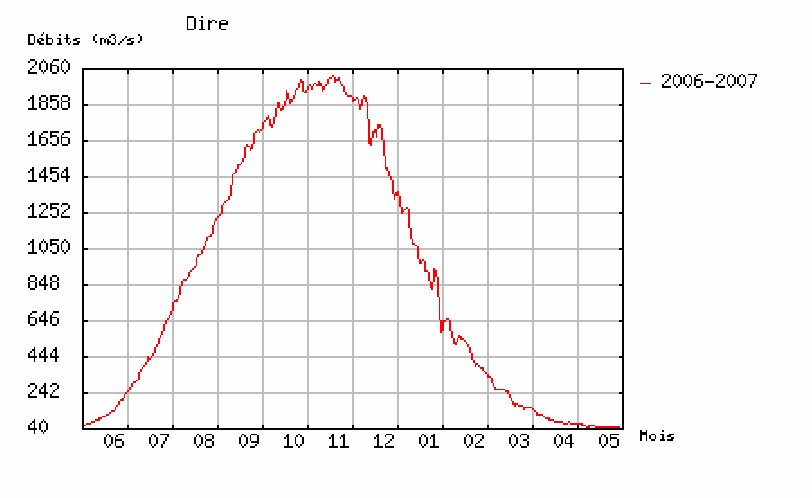
a)


Kouroussa
Débits (m3/s)
790
711
632
553
474
395
316
237
158
79
0
06 07 08 09 10 11 12 01 02 03 04 05
Mois
2006-2007

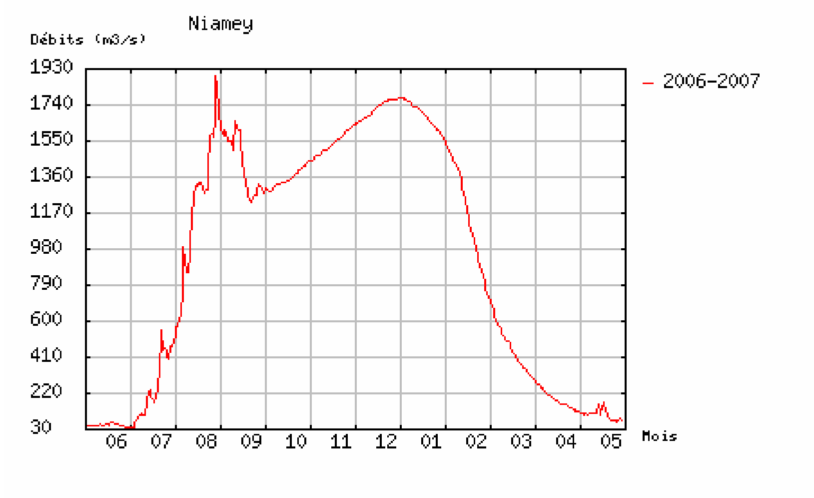
b)


Koulikoro
Débits (m3/s)
4210
3793
3376
2959
2542
2125
1708
1291
874
457
40
06 07 08 09 10 11 12 01 02 03 04 05
Mois
2006-2007

c)


Dire
Débits (m3/s)
2060
1858
1656
1454
1252
1050
848
646
444
242
40
06 07 08 09 10 11 12 01 02 03 04 05
Mois
2006-2007

d)


Niamey
Débits (m3/s)
1930
1740
1550
1360
1170
980
790
600
410
220
30
06 07 08 09 10 11 12 01 02 03 04 05
Mois
2006-2007

e)

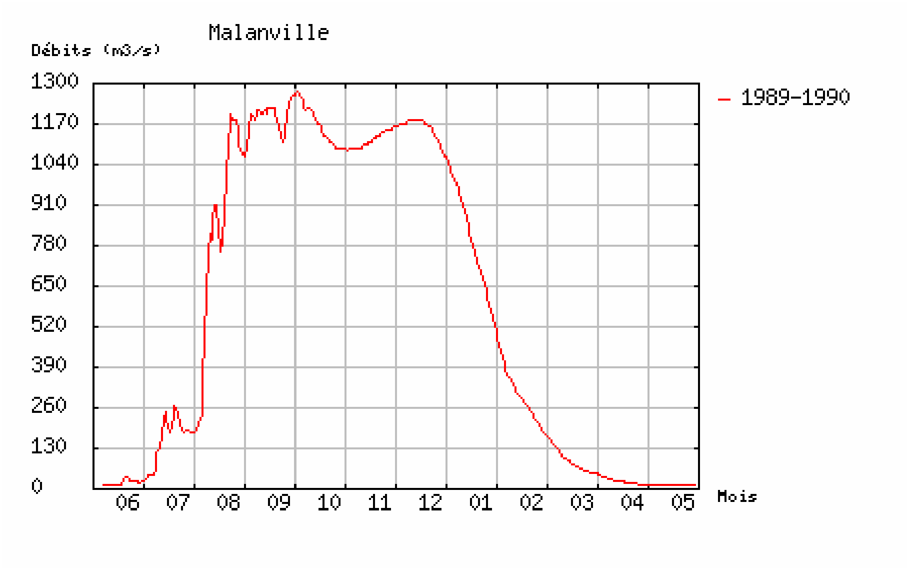


Figure IV- 5: Characteristic hydrographs of the Niger River from Kouroussa to Malanville

1.2. Physical characteristics of the middle Niger River basin

1.2.1. Definition and main characteristics of the middle Niger basin

The middle Niger River is the term used to describe the section of the River Niger between the "interior delta" at Diré and an arbitrary limit at the Niger-Nigeria frontier [*Y Brunet-Moret et al.*, 1986], other authors like Rodier [1964] have defined its downstream limits to be the confluence of the Niger and Benue rivers at Lokoja in Nigeria.

The middle course of the Niger River is characterized by relatively low precipitation and limited tributary contribution to the Niger's flow discharge.

Like most tropical rivers, precipitation is the major controlling factor of middle Niger River's flow, with evaporation and infiltration effects being of secondary importance.

The middle Niger's tributaries are seasonal, with runoff from May/June to October/November depending on the prevailing climatic factors for each tributary's basin, although base flow may continue up to January. In contrast to its tributaries, the Niger is a perennial river and has only been intermittent for a few days in periods of severe drought in 1974 and 1985 at Niamey for the entire period on record (1929 - 2008).

1.2.2. The importance of the tributaries of the Middle Niger River

The middle section of the Niger River is of particular interest, in terms of water and sediment input, because it is the stretch where the Niger River receives its first tributaries after the losses that occur in its interior delta. One particularity of the middle Niger River is the fact that between its exit from the interior delta and Gaya near the Niger-Nigeria frontier, it only receives tributaries from its right bank as most of the former tributaries on its left bank are now inactive, like the Dallol Bosso and Dallol Maouri, and hardly sustain runoff to the Niger River. The name "Dallol" is used to designate dry valleys usually characterized by their large width and gentle slopes [*P Chaperon*, 1971].

The middle Niger River receives three tributaries along its course up to Niamey; the Gorouol, the Dargol and the Sirba. Downstream of Niamey, the Niger River receives five more tributaries before the Niger-Nigeria border, the Goroubi, the Diamangou, the Tapoa, the Mékrou, the Alibori and the Sota.

The basin characteristics of the main tributaries of the middle Niger River are summarised in Table IV- 4

Table IV- 4: Tributary Characteristics (Middle Niger River)

River	Basin Area (km²)	Altitude(m)
Gorouol	45125	240 - 320
Dargol	7200	200 - 320
Sirba	38750	200 - 320
Goroubi	15500	200 - 320
Diamangou	4400	200 - 280
Tapoa	5500	200 - 280
Mékrou	10690	180 - 650
Alibori	13650	180 - 360
Sota	12100	240 - 320

The present study focuses on the Gorouol, the Sirba and the Mékrou Rivers, and their geological, soil and vegetation characteristics are described in part I. Brunet-Moret et al. (1986) describes the other tributaries.

- **The Gorouol River** with a basin size of about 45000 km² and altitude ranging from 240 m to 320 m is the first of the middle Niger's tributaries. The Gorouol basin is located in three countries: Mali, Niger and Burkina-Faso. Mean annual precipitation between 1950 and 1990 over the Gorouol basin ranged from 300 mm to 500 mm. As observed in part III of this work, barrages and water retention basins are located on the Gorouol basin and this could have an effect on the hydrology and transfer of sediment from this basin to the middle Niger River. The Gorouol basin is presented in Figure IV- 6.

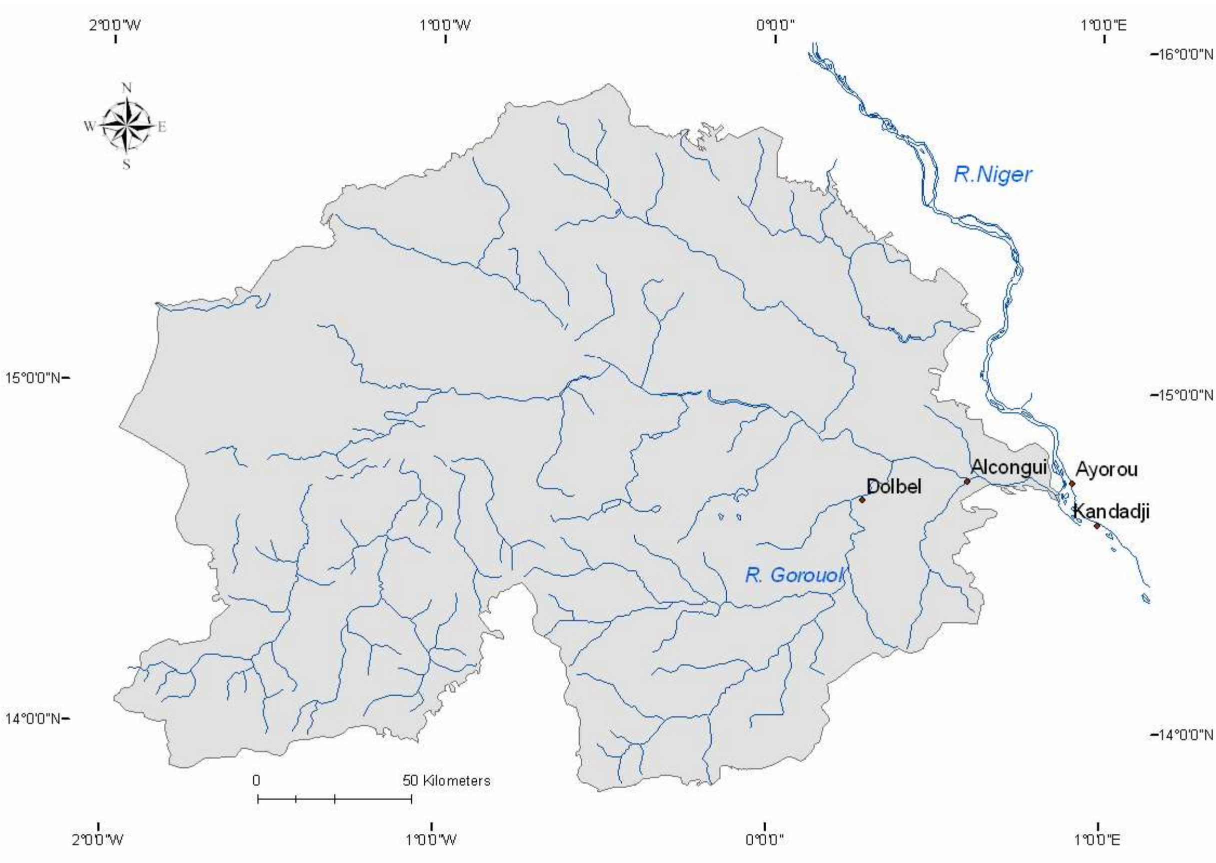


Figure IV- 6: The Gorouol Basin

- **The Sirba River** has a basin area of 38750 km² and altitude ranges from 200 m to 320 m with gentle slopes. The Sirba basin is located in Burkina-Faso and Niger, with a large part of its upper basin in Burkina-Faso. The Sirba River has a dense network of tributaries and receives a mean annual precipitation greater than 500 mm (1950 - 1990 data) making it a significant tributary of the middle Niger River. Barrages and water retention basins exist particularly in the upstream part of the Sirba River and may affect the river discharge and sediment transfer dynamics closer to the Sirba's confluence with the Niger River. The Sirba basin is presented in Figure IV- 7.

Figure IV- 7: The Sirba basin

* **The Mékrou River** has a basin size of about 10769 km² and has a simple network without any major tributaries. The Mékrou basin is located mainly in the republic of Benin and in Niger. Steep slopes and such features as waterfalls, gorges, and rapids characterize the Mékrou basin. Annual precipitation is between 1350 mm upstream, and 750 mm near its confluence with the Niger River. A single peak that usually occurs between August and September characterizes the Mékrou River's discharge. The Mékrou basin is presented in Figure IV- 8.

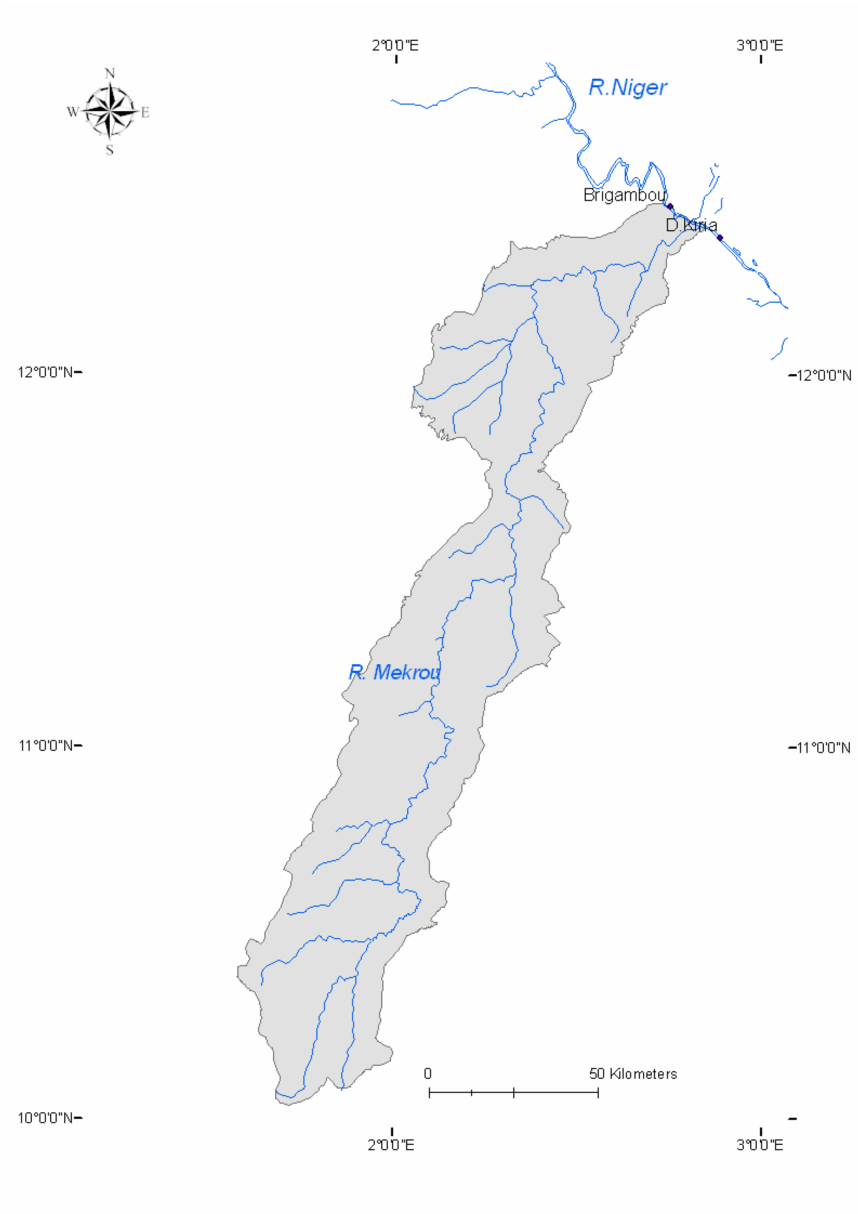


Figure IV- 8: The Mékrou basin

1.3. Variability of river discharge in the middle Niger River basin

1.3.1. River discharge dependence on precipitation

Rodier and Roche[1978] defined semi-arid regions, with respect to the Sahel, as regions with a rainfall limit of 500-600 mm and mean annual temperature above 18°C.

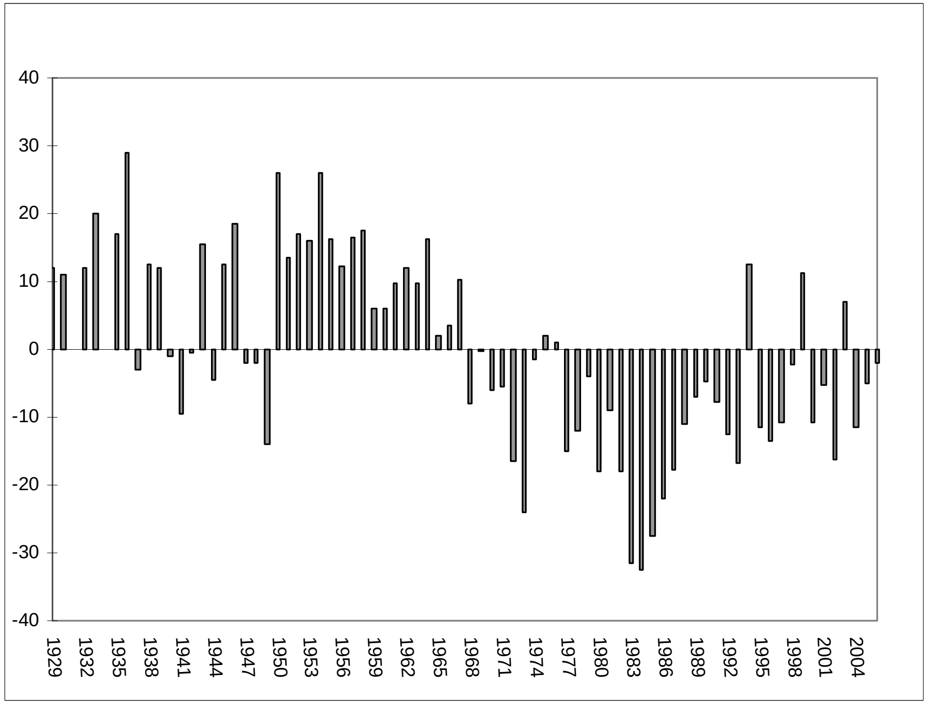
The middle Niger River and its tributaries are located in the southern Sahel and Sudan I regions and are mainly influenced by the Sahelian and pure tropical regimes. The influence of the two different regimes is observable on the Niger River at Niamey, where there are two peaks, the first one being due to the tributaries of the Sahelian regime and the second peak due to the upper Niger River of the tropical transition regime.

Rainfall in the middle Niger basin demonstrates a high variability in time and space and appears to follow a cyclical trend of wet and dry periods. The Niger River's regime being climate dependent is influenced by changes in climatic factors such as precipitation as well as associated physiographic changes such as land cover and basin runoff coefficient.

Mahé et al. [2003] highlighted what they described as a post-1973 phenomenon of increased runoff in spite of a reduction in rainfall in "sudano-sahel" areas with less than 700 mm of annual precipitation. In areas of the sudano-sahel with more than 700 mm of annual rainfall, they found runoff to vary directly with rainfall. In the non-sahelian part of West Africa, Paturel et al.[1997] observed a cyclical trend in variations around mean precipitation values between 1925 and 1990, with the most severe deficit period occurring around 1970. Lubès-Niel et al.[2001] observed a change in the form and intensity of hyetographs for rainfall data at Niamey before and after 1969 for data between 1956 and 1998.

River discharge in the middle Niger basin is strongly dependent upon precipitation. A comparison of percentage departure from the mean for precipitation and cumulative annual volume discharge for the middle Niger basin is shown in Figure IV- 9(a) and Figure IV- 9(b) for the period between 1929 and 2006. The precipitation data is for the Niger River basin upstream of Niamey and was calculated by combining standardized precipitation indices derived by Olivry et al. [1993] and by Ali and Lebel [2008] The river discharge data is for the Niger River at the Niamey station. The strong rainfall dependence of river discharge is apparent but furthermore is amplified by a factor of two particularly in periods of low precipitation.

a)



b)

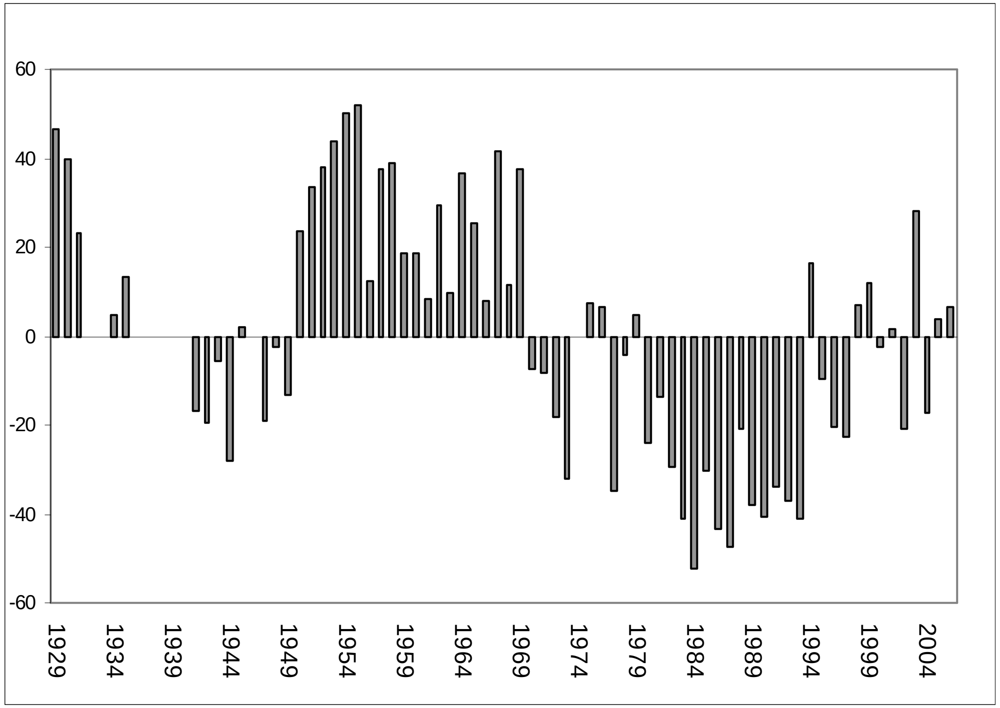


Figure IV- 9: Percentage departure from mean values of (a) precipitation over the Upper and Middle Niger basins, (b) cumulative annual discharge of the Niger River at Niamey.1929-2006

The direct relationship between precipitation (for the Niger basin upstream of Niamey) and river discharge for the Niger River basin at Niamey is illustrated in Figure IV- 10.

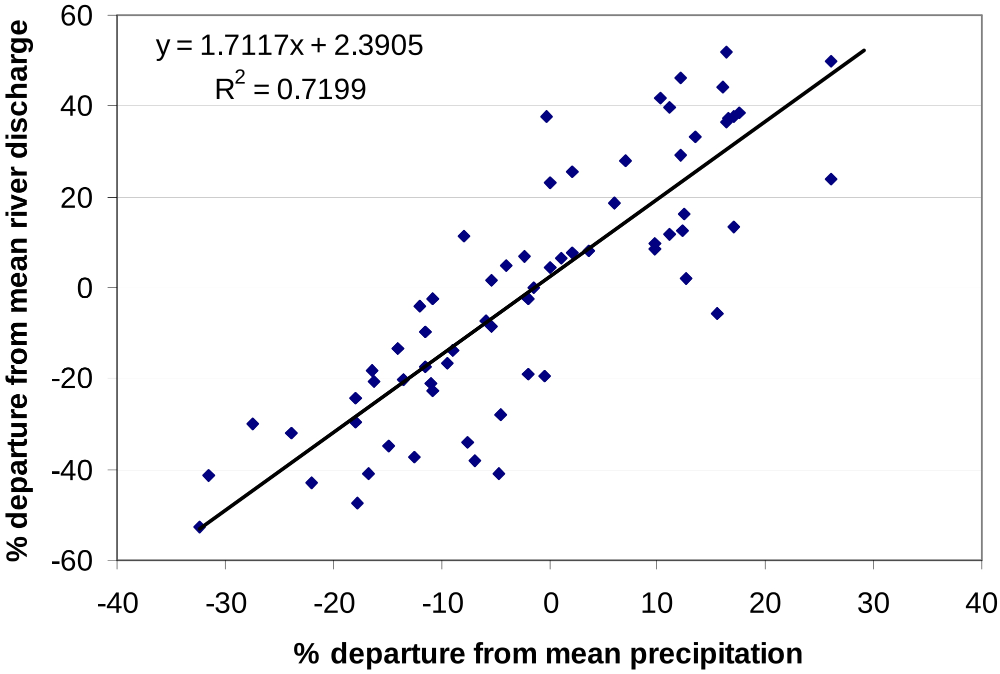


Figure IV- 10: Relationship between precipitation and river discharge indices

1.3.2. Inter-annual variability in river discharge of the middle Niger River

The maximum record discharge of Niger River at Niamey for the period of record (1929-2007) was 2360 m^3/s and a minimum discharge of zero m^3/s occurred in years of extreme drought.

The values for annual maximum and minimum record discharge between 1929 and 2007 for the Niger River at Niamey are presented in Figure IV- 11. The cyclical trend of wet years and dry years is repeated for both the maximum and minimum flows. Figure IV- 11 shows that between 1972 and 1991, the low flows at Niamey were near zero, but have maintained a non-negligible level thereafter. The Sélingue dam constructed in 1981 on the Sankarani River (a tributary of the Niger River) upstream of Koulikoro, has been used to regulate low flows on the Niger River [*M Kuper et al.*, 2002]. The regulatory role of this dam on low flows can be observed after 1991 in Figure IV- 11.

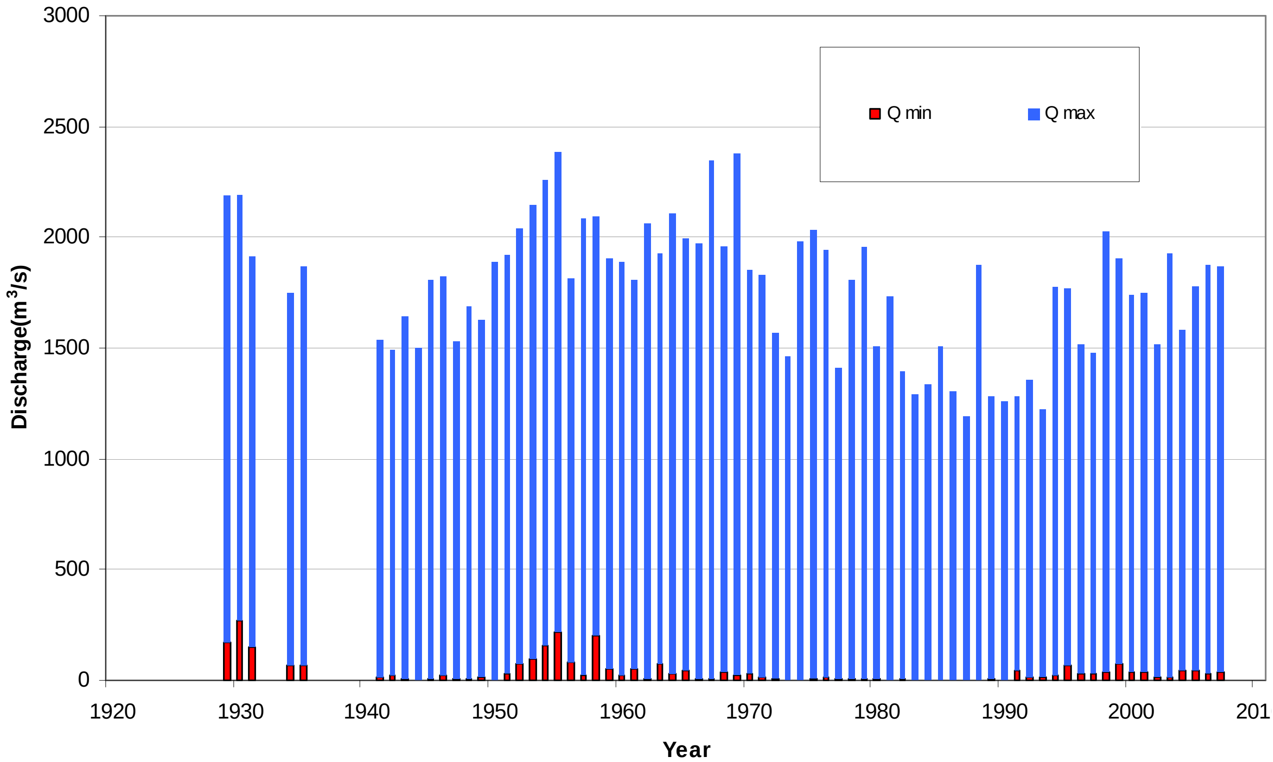


Figure IV- 11: Annual minimum (Q_{MIN}) and maximum (Q_{MAX}) daily mean discharge of the Niger River at Niamey (1929/30 – 2007/08)

An analysis of the Niger River's flow duration characteristics at the Niamey station between 1929 and 2006 was carried out using daily discharge data. In addition to the total record period, the analysis was extended to other periods of interest such as the wet and dry spells, as well as the years of recorded extreme values in terms of daily discharge and cumulative annual discharge volume (See appendix D for Figure D- 1 to Figure D- 7).

A summary of the flow duration characteristics of the River Niger at Niamey is presented in Table IV- 5 indicating for each period, the prevailing discharge for 5%, 50%, and 95% of the time. Low flows occur at discharge values below the median value (the discharge equalled or exceeded 50% of the time) while high flows occur at values greater than the median value. The significance of each period chosen is summarized in the remarks column of Table IV- 5.

The Q_{90}/Q_{50} ratio is commonly used as a base flow index to indicate the proportion of stream flow due to ground water storage [*R J Nathan and T A McMahon*, 1990]. The base flow component of river discharge which is dependent upon such basin characteristics as climate, vegetation cover, land use, soil type and geology, is significant when the slope of the low flow portion of the flow duration curve is low (high values of the Q_{95}/Q_{50} index). High values of the Q_{95}/Q_{50} index reflect continuous discharge to the river from natural storage.

Table IV- 5: Flow duration characteristics of the Niger at Niamey

Year/Period	% of time that indicated discharge(m^3/s)was equalled or exceeded			Q_{95}/Q_{50}	Remarks
	5%	*50%*	*95%*		
1929/30-2006/07	1600	800	10	0.0125	Entire record*(72yrs)
1950/51-1969/70	1800	900	40	0.0444	Wet spell
1956/57	1400	910	80	0.0889	Year of maximum annual discharge volume
1969/70	2100	1100	18	0.0164	Year of maximum daily flow
1970/71-1989/90	1500	450	4	0.0089	Dry spell
1984/85	980	155	4	0.0258	Year of minimum annual discharge volume
1985/86	1200	280	0.04	0.0001	Year of minimum daily flow

**(data for 1932/33 and 1936/37 to 1940/41 were unavailable)*

It can be observed from Table IV- 5 that base flow contribution to the Niger's discharge was highest in 1956/57 when the Niger discharged its record maximum volume at Niamey. By 1985/86, base flow contribution was greatly diminished. The Niger River's annual discharge volume in 1984/85 was the lowest on record, while the minimum daily discharge of zero m3/s was recorded in 1985/86. The fall in the Q95/Q50 index for the consecutive years suggests a depletion of the natural storage during these years.

The above analysis highlights the variability of the Niger's discharge at Niamey between 1929 and 2008, in periods of high discharge and periods of low discharge or droughts.

1.3.3. Definition of drought and high flow periods for the middle Niger River

The definitions of drought are as different as the professions that study the phenomenon. The basic concept of droughts is associated with a period of low or below normal water supply with respect to water or moisture requirements, making droughts climate dependent.

The appropriate definition depends on the field of study and component(s) of interest such as stream flow, reservoir storage, precipitation, and soil moisture. For the present study, a characterization of stream flow is important in order to study the effects, if any, of periods of below average water supply on sediment production and transport.

A threshold value is necessary to define drought periods and to distinguish them from other events. Dracup [1980] suggests three fundamental descriptors of drought events; severity, magnitude and duration and they are related by the expression *S=M*D*.

Where: S, severity = cumulative deviation from X_0

M, magnitude = average deviation from X_0

D, duration = time between successive crosses of X_0

The drought periods are described as a function of the mean annual runoff volume X_0 for the discharge series. X_0 is known as the truncation level and divides the series into "above normal" and "below normal" sections. A plot of the departures from the mean annual volume discharged by the Niger River at Niamey between 1929 and 2008 (with a few years of missing data) is presented in Figure IV- 12, highlighting the magnitude and severity of high and low flow periods. The values for drought magnitude are presented in Figure IV- 12 as a ratio of the mean annual volume discharged, and thus range from -1 to 1., with negative values representing droughts and positive values representing periods of high river discharge.

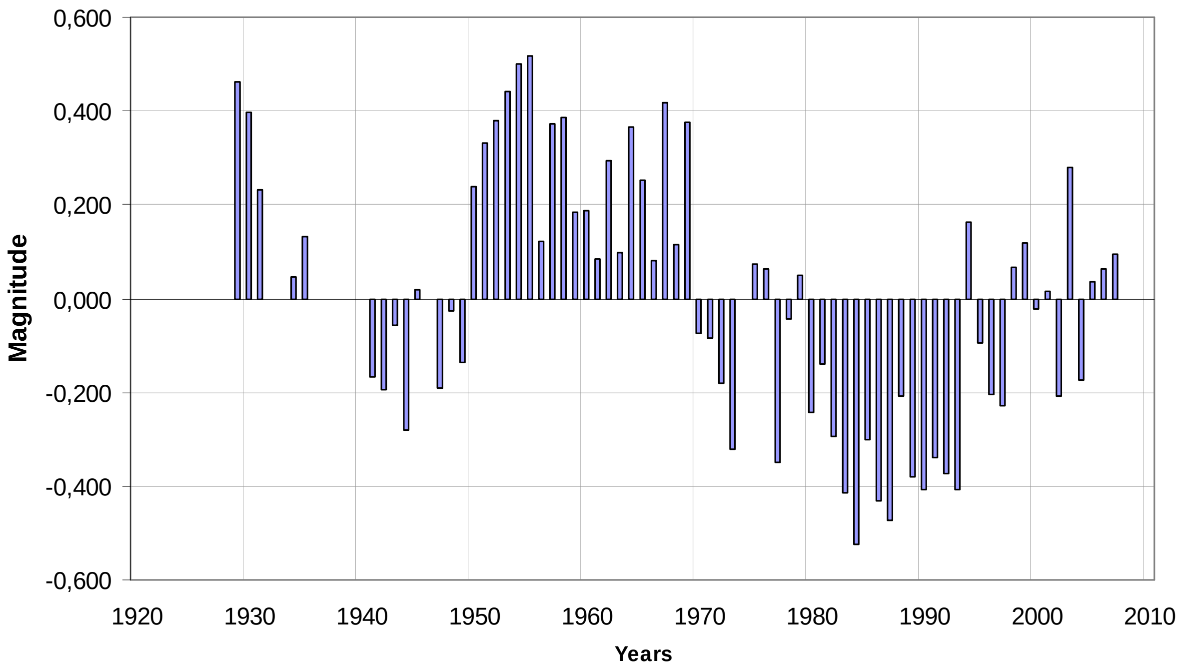


Figure IV- 12: Drought characterisation of river discharge of the Niger at Niamey (1929/30 to 2007/08) based on annual volume discharged

The discharge record of the Niger River at Niamey can therefore be divided into twenty distinct periods across the drought threshold value. The periods and the severity of either high flow (positive values) or low flows or droughts (negative values) are indicated in Table IV- 6.

Table IV- 6: Relative severity of drought periods between 1929 and 2007

	Period	Severity	Ranking of above normal periods	Ranking of below normal periods
1	1929-1931	1.092	2	-
2	1934-1935	0.178	6	-
3	1941-1944	-0.696	-	2
4	1945	0.020	10	-
5	1947-1949	-0.351	-	6
6	1950-1969	5.748	1	-
7	1970-1974	-0.661	-	3
8	1975-1976	0.139	8	-
9	1977-1978	-0.391	-	5
10	1979	0.049	9	-
11	1980-1993	-4.939	-	1
12	1994	0.162	7	-
13	1995-1997	-0.528	-	4
14	1998-1999	0.187	5	-
15	2000	-0.023	-	9
16	2001	0.015	11	-
17	2002	-0.208	-	7
18	2003	0.280	3	-
19	2004	-0.174	-	8
20	2005-2007	0.195	4	-

The values are plotted in Figure IV- 13 highlighting the major periods of high discharge (1950-1969) and low discharge or drought (1980 -1993) according to Table IV- 6.

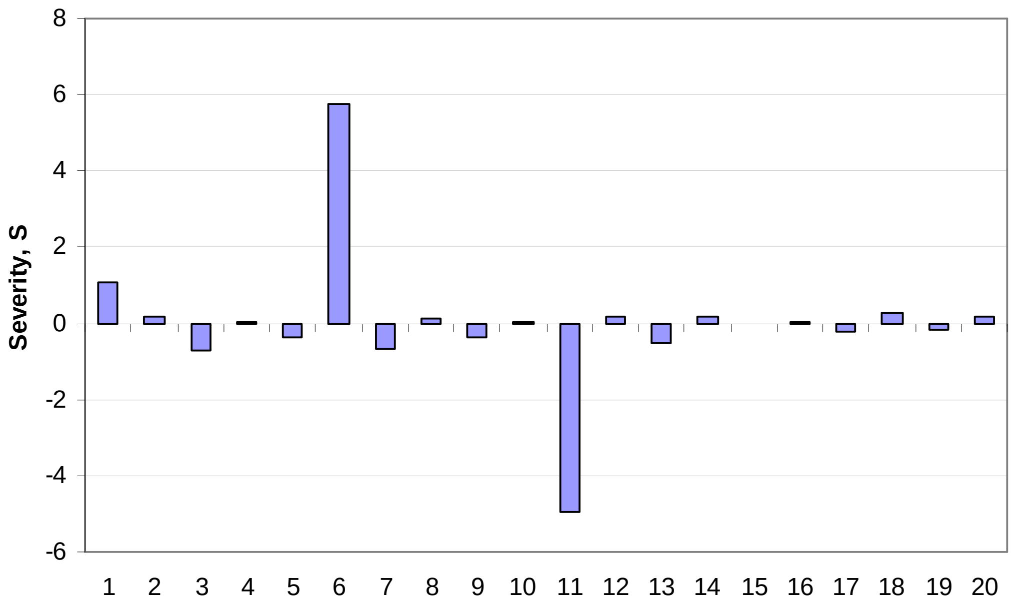


Figure IV- 13: Relative severity of high and low flow periods for the Niger River at Niamey (1929-2007)

In order to compare the average hydrographs of relatively smaller sample size of representative periods of "above normal" and "below normal" river discharge, four periods can be identified from Figure IV- 12 and Table IV- 6:

- Two periods (1929 to 1935 and 1950 to 1969) with annual discharge volumes greater than the long-term average;
- Two periods (1941 to 1949, and 1970 to 2007) with annual discharge volumes less than the long-term average.

The mean hydrographs for the four periods are presented in Figure IV- 14 below.

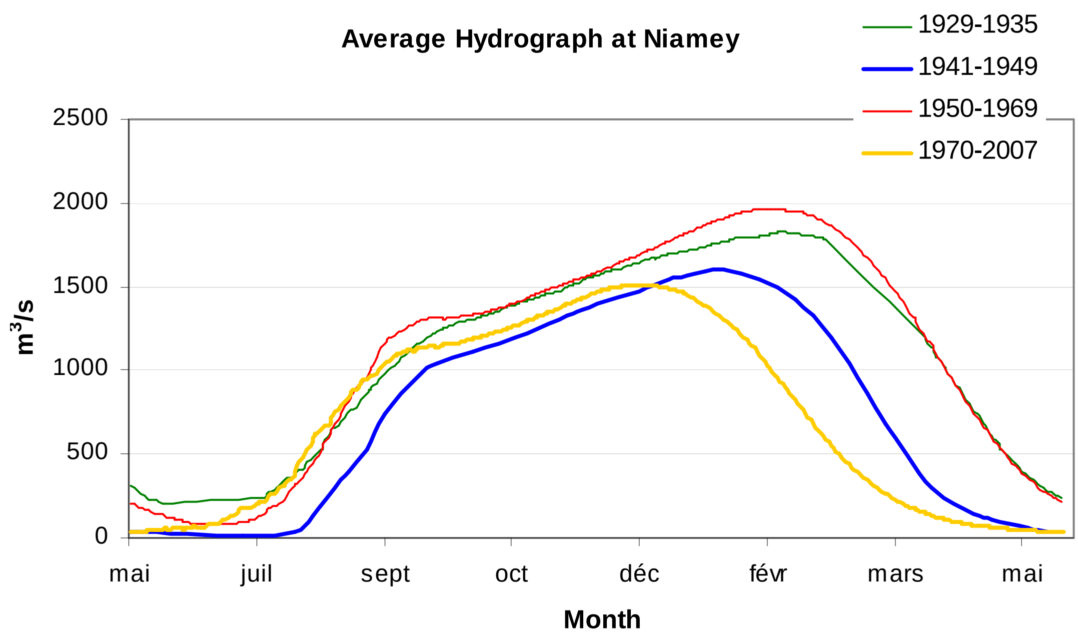


Figure IV- 14: Average hydrographs of the Niger River at Niamey

The average hydrographs for the two "above normal" periods, 1929-1935 and 1950-1969 are nearly identical, except for the fact that the low water discharge is more severe and the peak discharge is higher for the 1950-1969 period which could be an early effect of land use and land cover change. However, the quality of data may be questioned for earlier dates particularly because data does not exist for the some years between 1932 and 1941 (see Figure IV- 12). In addition, an evaluation of the runoff coefficients of these two periods would need to be made for this assertion to be valid, especially because environmental data for the earliest period may be inexistent.

A comparison of the two "below normal" periods 1941-1949 and 1970-2007 reveals that the Niger at Niamey now peaks about 32 days earlier (1970-2007) compared to 1941-1949. Furthermore, the Niger's mean annual discharge peak is now (1970-2007) about 100m^3/s lower than the last "below normal" discharge period (1941-1949). The most severe period of drought in terms of river discharge occurred for the Niger at Niamey between 1980 and 1993, as can be observed in Figure IV- 13. A comparison of the average hydrograph for this period with the average hydrograph of the long-term low flow period of 1970-2007 in Figure IV- 15 illustrates the severity of the drought that occurred between 1980 and 1993. The average maximum discharge between 1980 and 1993 was almost 200m^3/s less than for the period between 1970 and 2007.

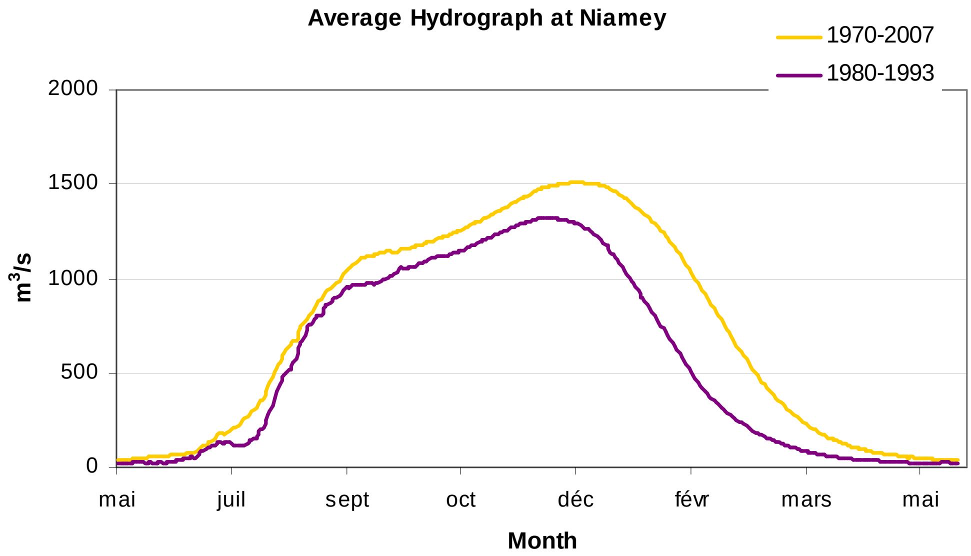


Figure IV- 15: Average hydrographs of the Niger River at Niamey

1.3.4. Change in Middle Niger River input: the Sirba example

An analysis of discharge data of the Sirba River between 1956 and 2008 indicate a trend of increasing annual cumulative discharge that in turn has an impact on the Sirba's percentage contribution to discharge of the Niger at Niamey as shown in Figure IV- 16 and Figure IV- 17.

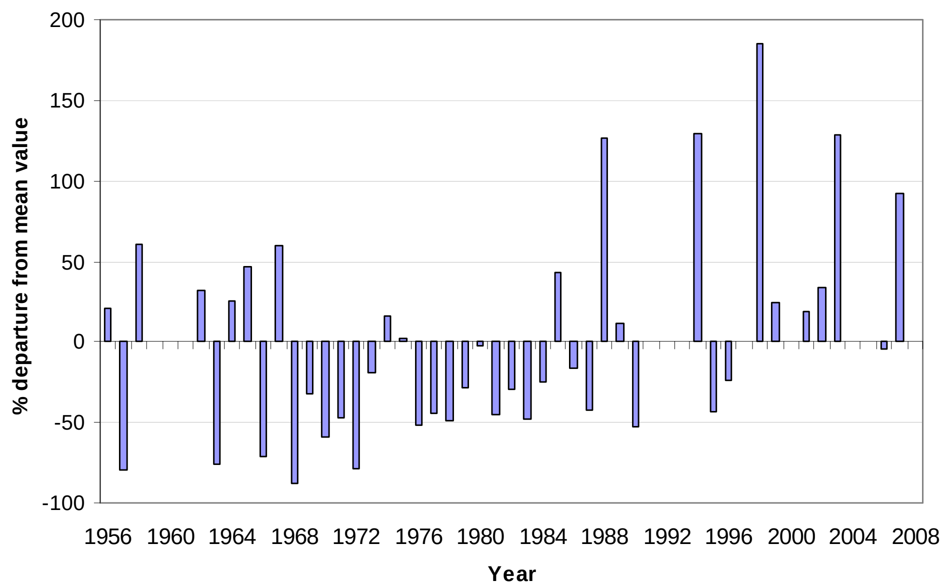


Figure IV- 16: Percentage departure from mean annual cumulative discharge for the Sirba River

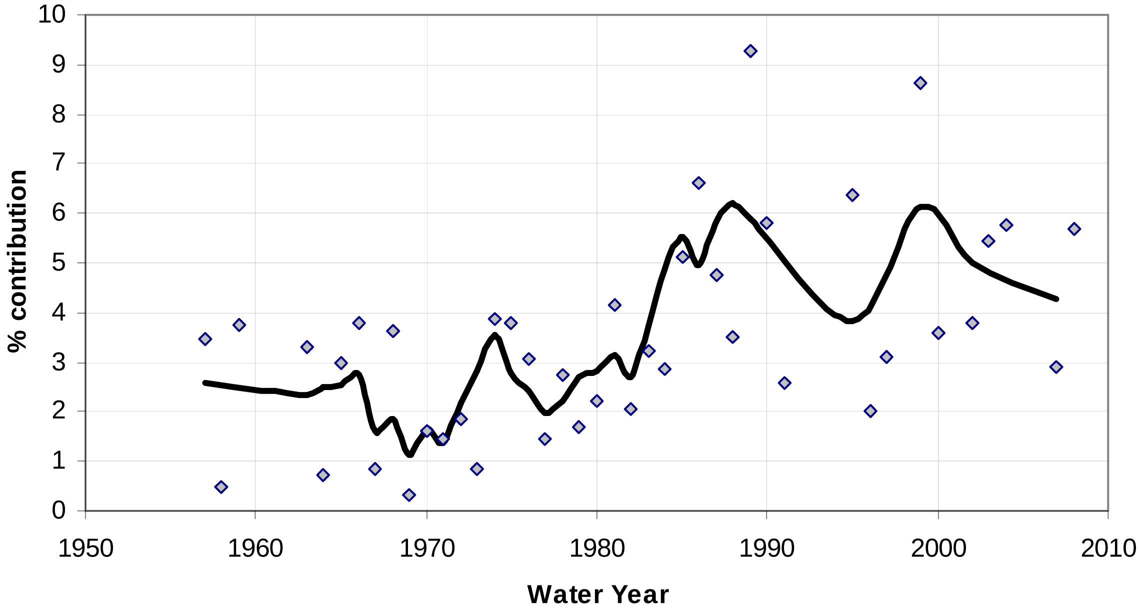


Figure IV- 17: Percentage contribution of the Sirba River to the middle Niger

The discharge record for the Sirba River at Garbé Kourou consists of only 42 complete years of record and in 18 of those years, the annual volume discharged by the Sirba where above the threshold of about 886 million m^3. The positive departures from the mean value between 1956 and 1967 (in Figure IV- 16) occurred at the same time as the positive departures from the mean values for precipitation and river discharge for the Niger River at Niamey (see Figure IV- 9). Since 1988, larger departures (up to 3 times the long term mean) of the volume discharged by the Sirba River at Garbé Kourou have occurred. This is in contrast to the Niger River's relative discharge that decreased during the same period. The effect of the slight recovery in precipitation in terms of the long-term average is manifest in the rise in annual volume discharged by the Sirba River. The cumulative annual discharge for the Sirba River shows a high variability ranging from just over 100 million m^3 in dry years to over 2500 million m^3 in years with high discharge. The cumulative annual discharge of the Sirba River at Garbé-Kourou was over 2 billion m^3 in the 1988/89, 1994/95, 1998/99 and 2003/04 water years.

Albergel [1987] studied the rainfall-runoff relationship on two experimental plots in Burkina Faso for a wet period (1950 – 1968) and for a dry period (1969 – 1984), and found that runoff was more favourable in the dry period, making up for the rainfall deficit experienced during the dry period.

Amani and Nguetora [2002] observed a modification in the Niger River's discharge regime at Niamey based on the discharge data between 1929 and 2000. They found that between 1970 and 2000 the Niger River at Niamey reached its peak discharge in December, in contrast to the period between 1928 and 1969 when the peak discharge was attained in February. They suggested that a reduction in water discharge from upstream areas of the Niger River coupled with increasing runoff coefficients in the middle Niger's sub-basins due to vegetation cover and soil degradation, were the causes of this change in discharge regime.

1.3.5. Water balance for a region of the middle Niger River basin: Inter-annual evolution of the water balance:

In order to evaluate the impact of the trend of increasing tributary flow and decreasing discharge of the input from the Upper Niger River, a water balance, in terms of annual cumulative river discharge, was carried out between two points on the middle Niger River; Kandadji and Niamey.

A comparison was made of the cumulative annual volume input of the Niger at Kandadji and its tributaries between Kandadji and Niamey (the Dargol River and the Sirba River) and the cumulative annual volume output (of the Niger River at Niamey) as illustrated in Figure IV- 18.

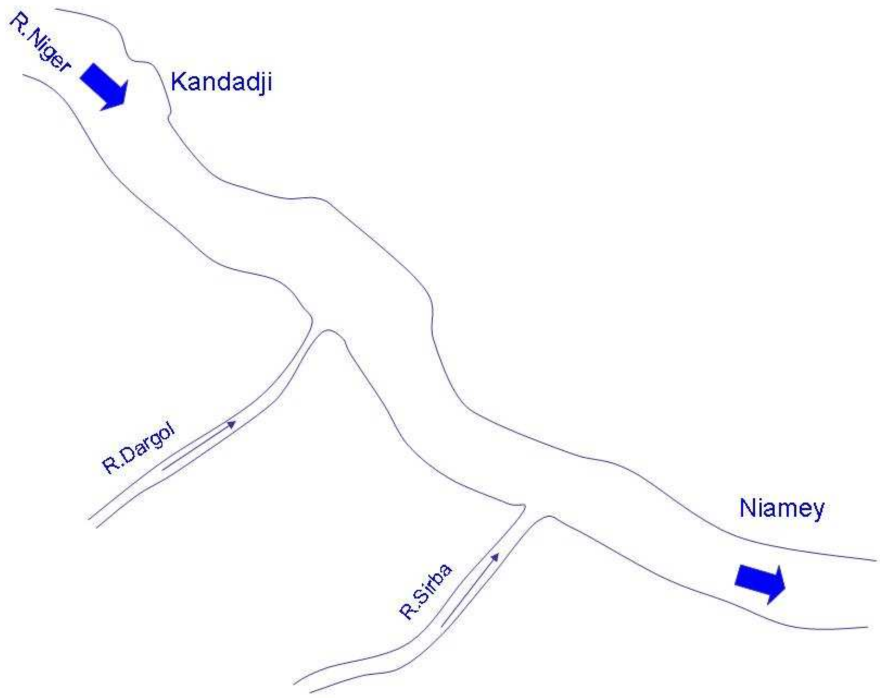


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Figure IV- 18: River Niger's discharge between Kandadji and Niamey

The data available for such a comparison between the two stations on the middle Niger River was for a total of twenty years between 1975 and 2007 as shown in Table IV- 7.

Table IV- 7: Water Balance between Kandadji and Niamey 1975/76 – 2007/08

Water Year	Sum of measured input($10^6 m^3$)	Measured output($10^6 m^3$)	Balance($10^6 m^3$)
1975/76	31733.0	29476.0	-2257.0
1976/77	31399.5	29169.8	-2229.7
1977/78	19381.3	17853.6	-1527.7
1978/79	27179.7	26264.6	-915.1
1979/80	28585.2	28747.6	162.4
1980/81	20680.2	20792.1	119.9
1981/82	24436.3	23595.2	-841.1
1982/83	20292.5	19349.4	-943.1
1983/84	16163.2	16100.0	-63.2
1985/86	20517.6	19146.3	-1371.3
1986/87	16986.6	15578.4	-1408.2
1987/88	15934.8	14442.4	-1492.4
1988/89	22419.7	21676.1	-743.6
1990/91	17941.6	16242.1	-1699.5
1991/92	21200.8	18096.4	-3104.4
1995/96	26722.8	24778.3	-1944.5
1998//99	28411.6	29263.7	852.1
2001/02	27124.0	27835.9	711.9
2006/07	28134.8	29166.7	1031.9
2007/08	26919.5	29969.8	3050.3

A plot of the difference between input and output in terms of annual cumulative water discharge between Kandadji and Niamey on the Niger River is presented in Figure IV- 19.

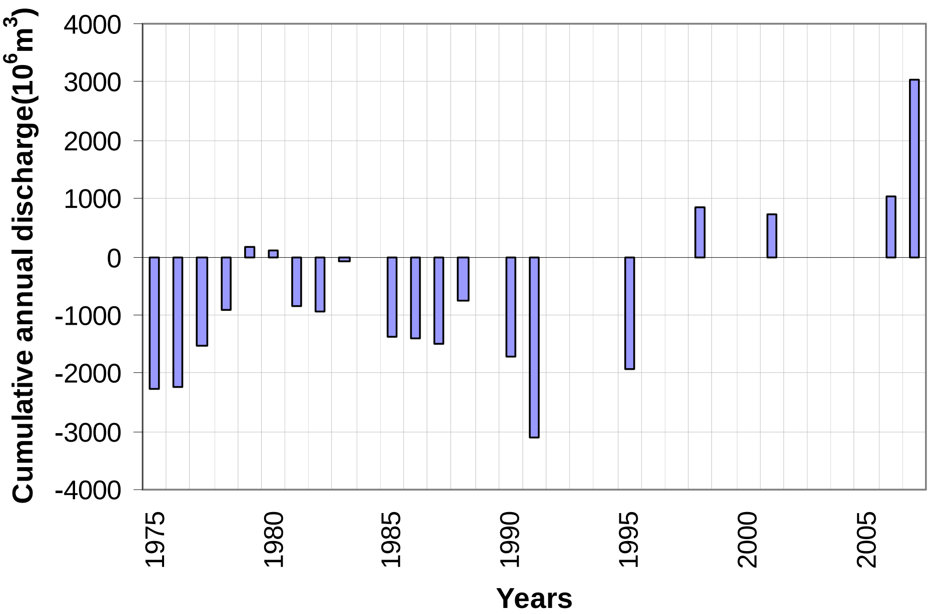


Figure IV- 19: Water balance between Kandadji and Niamey 1975 to 2008

Negative values in Figure IV- 19 occur when the annual cumulative discharge measured at Niamey is less than the sum of annual cumulative discharge of the Niger at Kandadji and the annual discharge volumes of the Dargol Sirba Rivers, while positive values indicate higher cumulative discharge at Niamey compared to all the upstream inputs as schematized in Figure IV- 20.

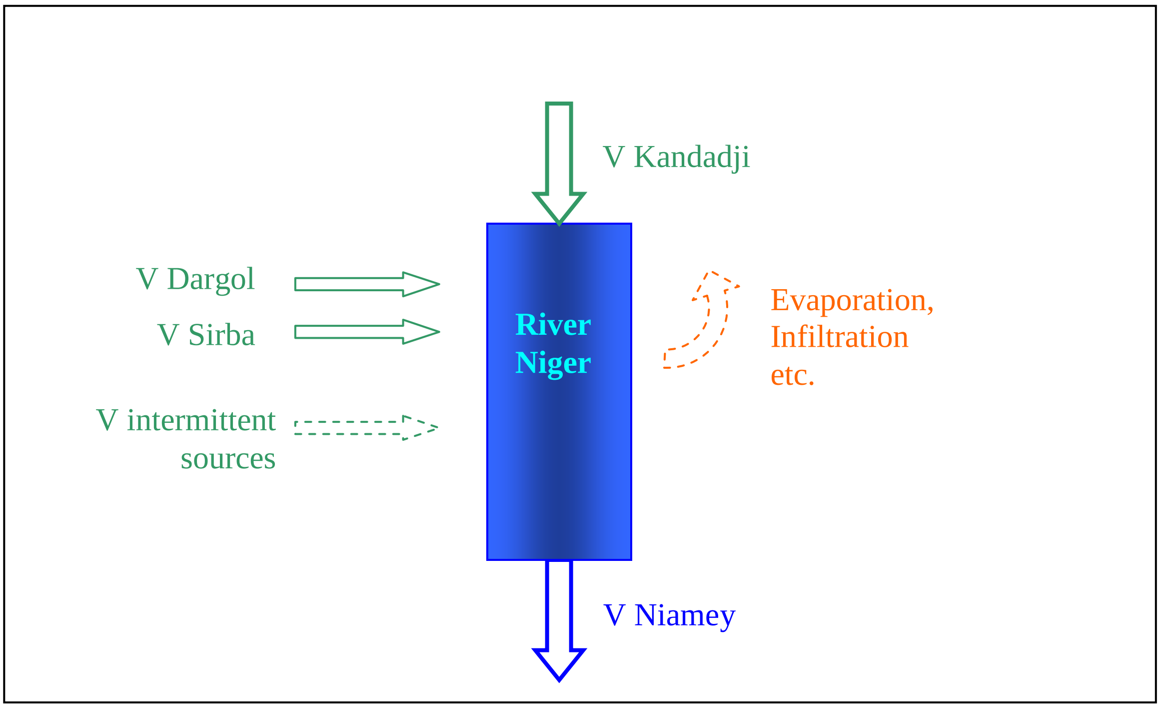


Figure IV- 20: Water balance for River Niger between Kandadji and Niamey

The input is the annual volume discharged at Kandadji plus the volumes discharged by the Dargol and Sirba rivers while the output is the annual cumulative water discharged by the Niger at Niamey plus losses. These losses are due to evaporation, infiltration, as well as water abstraction.

It was observed that in general, between 1975 and 1996 the input volume was greater than the output volume. Since 1998, for the years with complete discharge data, the reverse has been the case. The two periods are compared in Figure IV-21 showing that the peak discharge at Kandadji is reproduced at Niamey in December or January. This implies that the "surplus" volume discharged at Niamey is due to the more prominent first peak discharge period during the local rainy season (August to September) and not to measurement errors.

The evaporation and infiltration losses in a semi-arid region like the study area can be expected to be considerable. However, the observed "surplus" volume discharged by the Niger at Niamey is significant considering that the evaporation losses for the ~186 km reach between Kandadji and Niamey was estimated using data from the Food and Agriculture Organization's web LocClim estimator [*FAO*, 2008b] to be of the order of 764×10^6 m^3 per year (see Table D- 1 in appendix D).

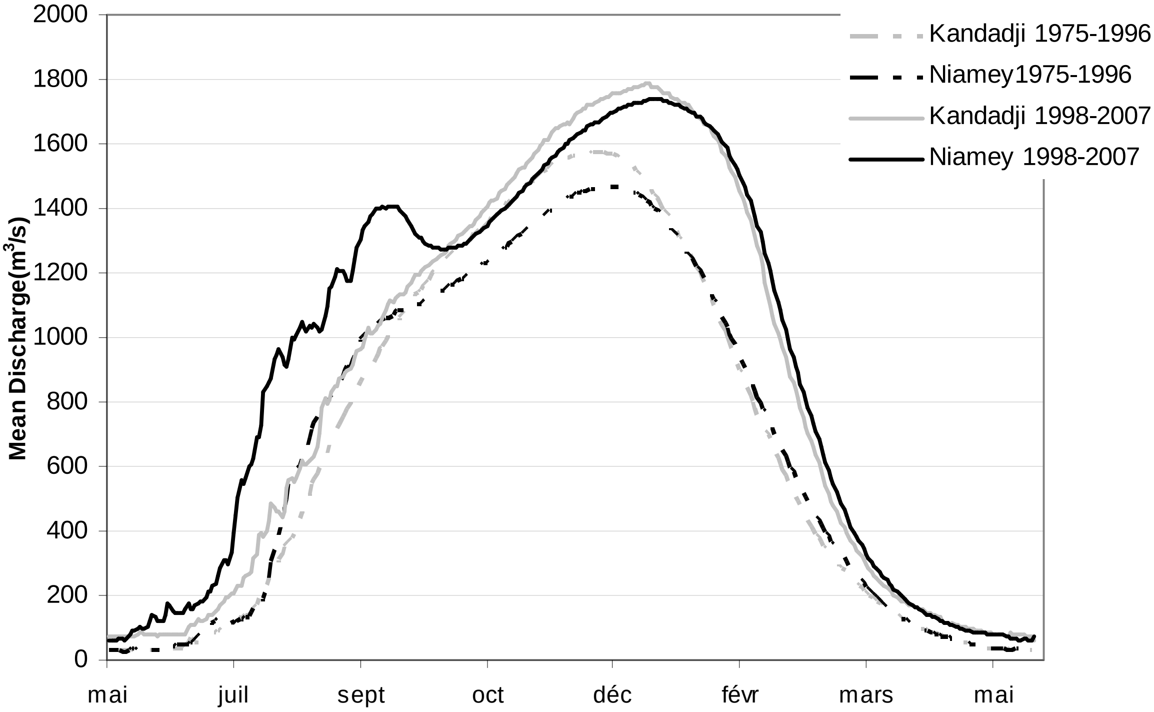


Figure IV-21: Comparison of the average hydrographs for the Niger at Kandadji and Niamey

The average hydrographs of the Niger at Kandadji and Niamey for the period between 1975 and 1996 have similar shapes in contrast with the hydrographs for the period between 1998 and 2007 where the tributary contribution to the Niamey hydrograph is apparent.

Several studies of the Sahelian hydrology have reported changes in response to climatic and human impacts. Amani and Nguetora [2002] suggested that the runoff coefficient of the middle Niger's tributaries could be increasing due to a reduction in vegetation cover. Mahé et al [2003] highlighted a "post 1973 phenomenon" of increased runoff in spite of a reduction in rainfall in mostly Sahelian areas with less than 700 mm of annual precipitation including most of the present study area. In areas of the Sudano-Sahel with more than 700mm of annual rainfall, Mahé et al. [2003] found runoff to vary directly with rainfall. A similar trend was noted by Séguis et al [2004] in Wankama on the mainly endorheic left bank of the Niger river with the runoff coefficient estimated to have increased by up to 1.7 times the value in 1950 in spite of the reduction in precipitation. Yero [2008] citing Esteves and Lapetite observed that runoff coefficient values at Tondikiboro, a Sahelian basin, had increased from 36% to 46% between 1991 and 2008 .

2. Focus on the study period: River discharge (measurement, estimation and hydrological context)

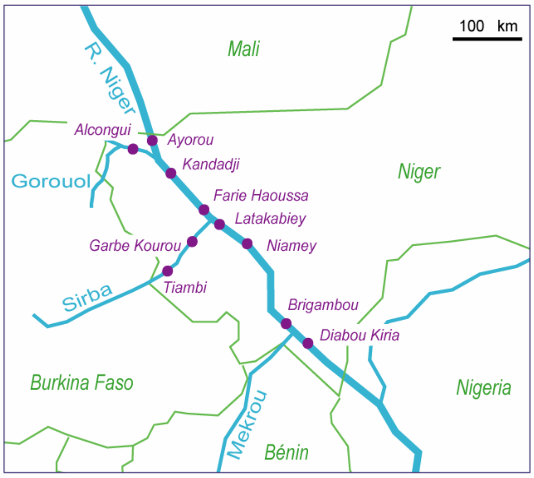
2.1. Measurement and estimation of river discharge

In order to estimate the sediment flux of the middle Niger River and its tributaries it was necessary to derive mean daily discharge data for the selected sediment measuring stations. These discharge values will be used in the sediment transport analysis in part V of this work to calculate sediment flux and to derive the parameters to evaluate the sediment transport capacity of the middle Niger River. Depending on whether the station was equipped with a means for measuring river discharge, discharge values were measured or estimated. The locations of the ten stations along the Niger River and its tributaries for which discharge data were derived are shown in Figure IV- 22.

2.1.1. At-station measurements

Measurement of discharge at stations equipped with staff gauges

At stations equipped with staff gauges, the daily mean river discharge was estimated by measuring the water levels twice a day and transforming these values to mean daily discharge in m^3/s. The River Niger Basin Authority provided the transformed discharge data for the stations at Kandadji, Niamey, W.Niger on the Niger River and Alcongui on the Gorouol River as well as Garbé Kourou on the Sirba River.



Estimation of discharge at other stations

The river discharge at Ayorou was estimated as the difference between the Niger's discharge measured at Kandadji and the discharge of the Gorouol at its confluence with the Niger River. The river discharge at Brigambou was assumed equal to that measured at the W.Niger gauging station close to Brigambou.

The discharge at Tiambi on the Sirba was estimated by multiplying the basin size ratio by the measured discharge at Garbe Kourou.

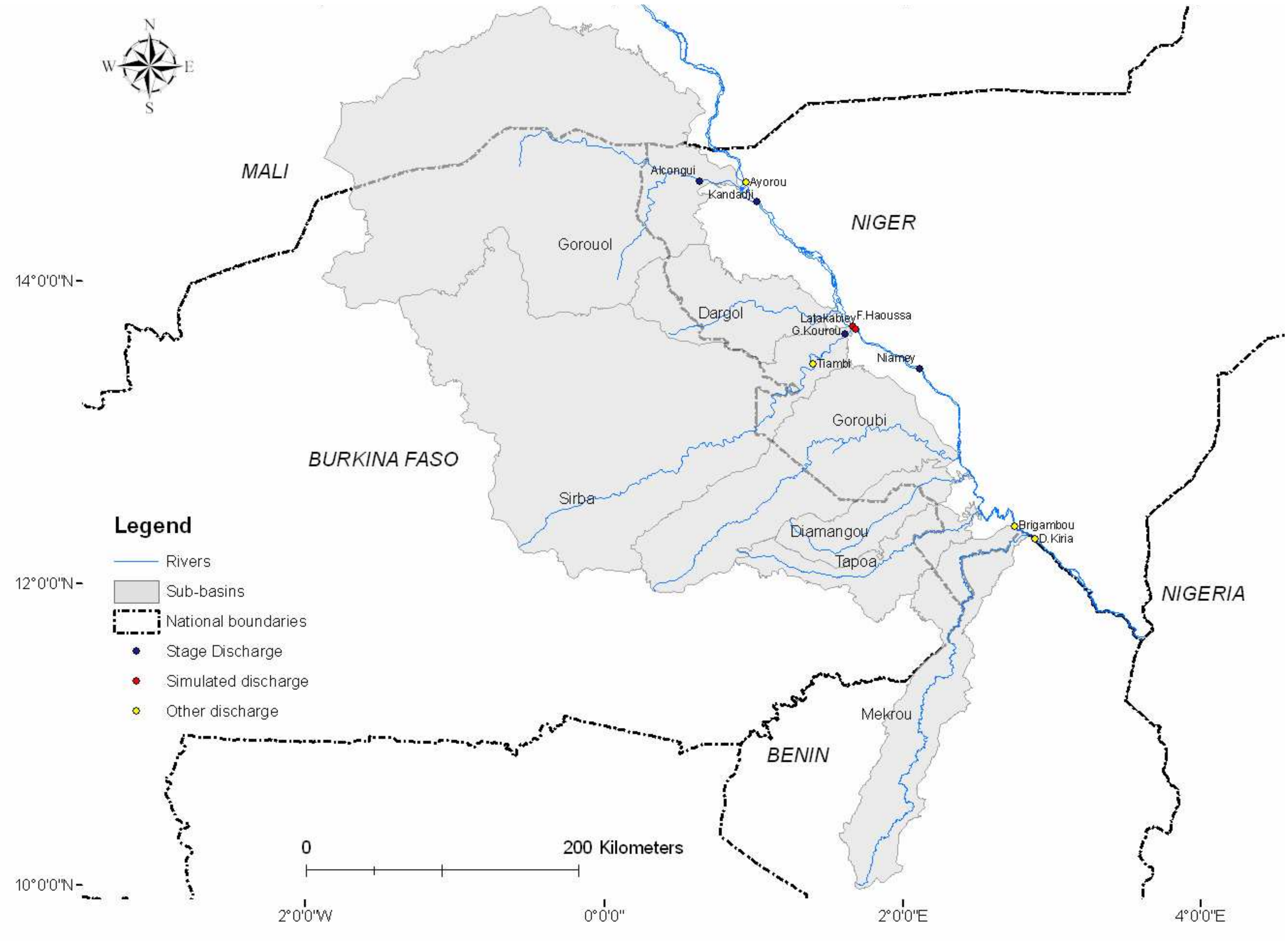


Figure IV- 22: Discharge measurements in the study area

2.1.2. 1-D modelling for the estimation of river discharge

The program

CARIMA (CAlcul de RIvieres MAillees) is a numeric code developed by SOGREAH consultants for open channel flow calculations in rivers and floodplains as well as for irrigation networks [*J A Cunge et al.*, 1980; *F M Holly and J B Parrish*, 1993].

It was designed to calculate two types of flow conditions, namely; 1-D flow in the principal channel by resolving the complete Saint-Venant equations, and flood plain flow (quasi 2-D flow) with simplified flow equations without the momentum term.

It is valid where flow conditions can be assumed to meet Saint-Venant's hypotheses:

- one dimensional flow, with uniform cross-sectional velocity;
- very small streamline curvature and hydrostatic pressure distribution;
- flow resistance and turbulence losses assumed to be the same as for steady uniform flow;
- small bed slope;
- constant water density.

The Niger River model: from Selingue to Malanville

A model of the Niger River from Selingue in Mali to Malanville in Bénin was designed by SOGREAH for the Niger River basin Authority. The model was developed from topographic measurements of the river's geometry in 1983, with the aim of simulating flood propagation along the measured stretch of the Niger River.

Initial and boundary conditions

Approximate initial conditions were set by the program and refined until a steady state was obtained. The boundary conditions were the Niger's hydrograph at Kandadji.

Objectives

The model is used for the following tasks

- Estimating the discharge at measurement stations that were not equipped with a flow gauge station (Farié-Haoussa and Latakabiey), by simulating flood propagation from an upstream station of known discharge.
- Estimating flow characteristics such as the energy gradient, surface velocity, bed shear velocity.

Assumptions and limitations

The major drawback of the use of the model described above is the fact that it has not been updated since 1983 and thus may not give reliable results that are within its original computational accuracy.

For the purposes of this study, it will be assumed that the model is able to furnish reliable information on flow conditions at the kilometre scale, despite local changes in channel geometry. Other information that can be provided by this model includes the flood propagation time, energy slope, flow depth, and mean surface velocity. The assumption made here will be tested in the following section.

2.1.3. Evaluation of the hydraulic modelling of river discharge

The results of the flood propagation simulation between Kandadji and Niamey are evaluated by a comparison of measured and simulated discharge at Niamey. The measured discharge at Niamey and in particular the rainy season peak discharges are well reproduced by the model. The largest observed deviations of the simulated values from measured values occur at intermediate discharge values. A plot of measured and simulated river discharge is presented in Figure IV- 23 and a plot of measured discharge against simulated discharge is presented in Figure IV- 24.

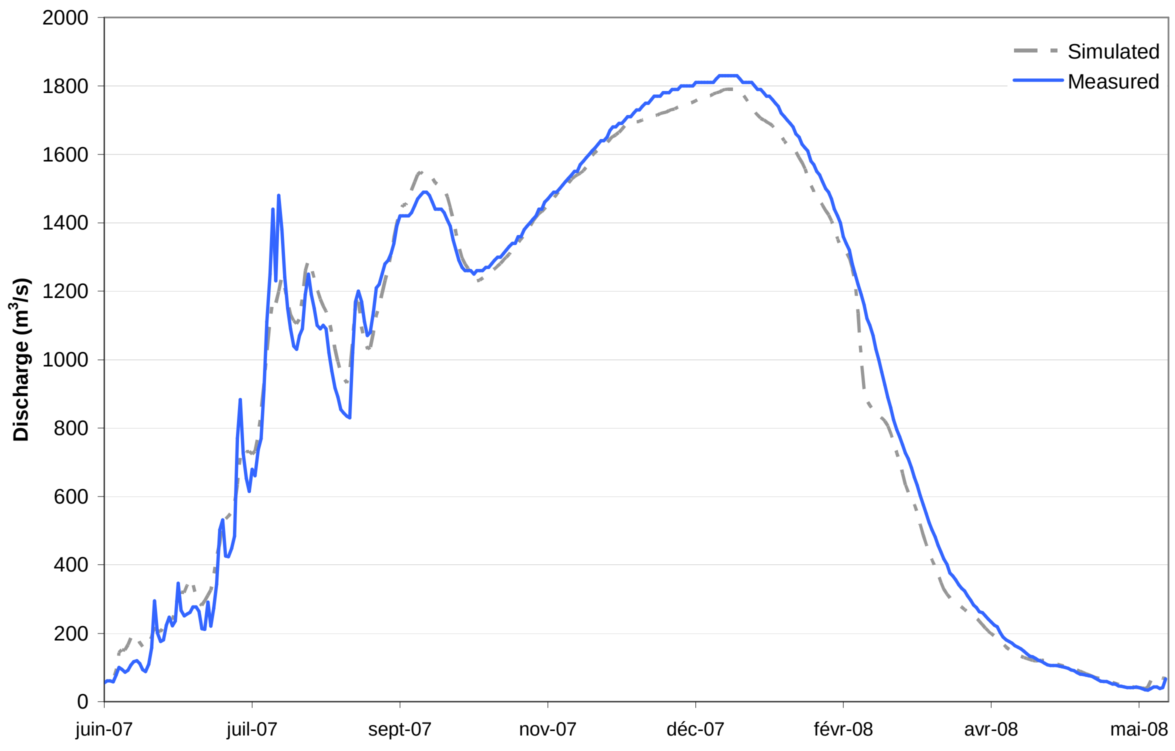


Figure IV- 23: Measured and simulated river discharge Niger at Niamey (June 2007 to May 2008)

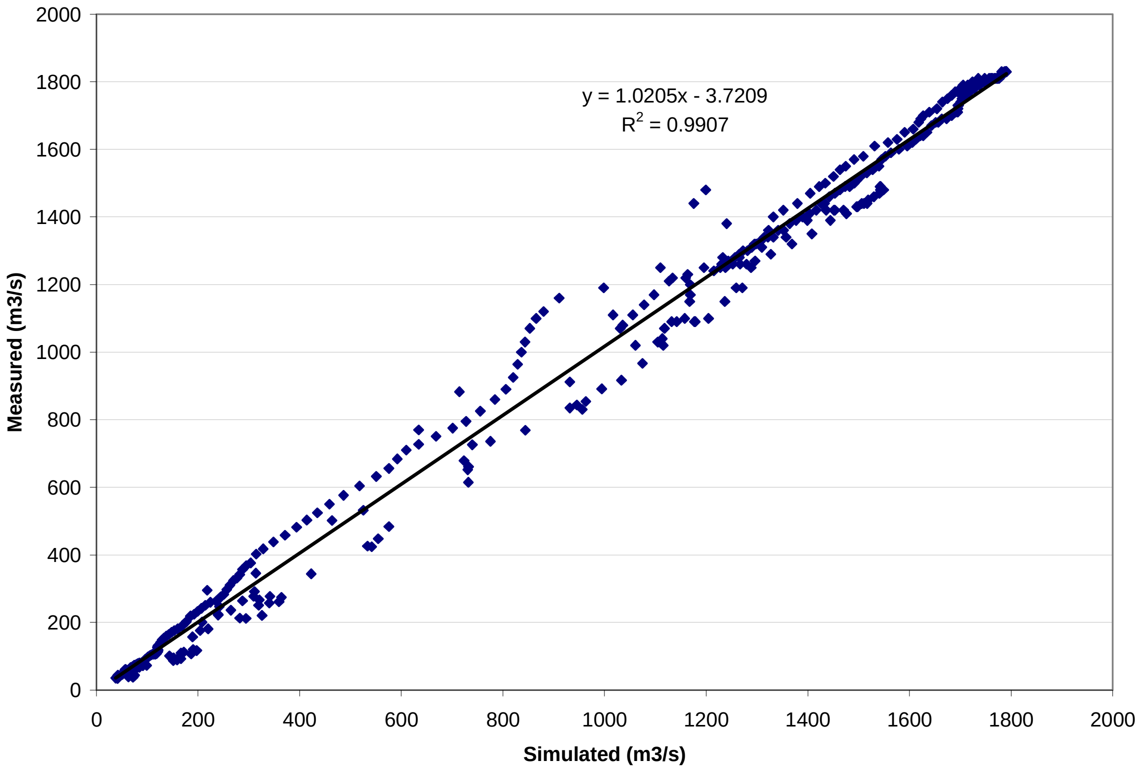


Figure IV- 24: Measured vs. simulated river discharge Niger at Niamey (June 2007 to May 2008)

In addition to providing river discharge values for ungauged stations along the Niger River, the model also provided the hydraulic data (energy gradient, depth of flow,) necessary for calculating the sediment transport capacity of the Niger River in part V of this work.

2.2. Hydrological context of the study period

The sediment sampling for the present study was carried out between 2005 and 2008. Previous sampling on the Niger at Kandadji (1976 to 1982) had been undertaken between by ORSTOM [*R Gallaire*, 1986].

The principal discharge characteristics for the middle Niger River are presented in Table IV- 8 for two representative gauging stations (Kandadji and Niamey) covering the periods that river suspended sediment concentration were measured. These characteristics include the annual mean discharge, maximum daily discharge, minimum daily discharge and the percentage of water volume discharged during the local rainy season (June to October).

Table IV- 8: River discharge characteristics of the Niger at Kandadji and Niamey

Station	Year	Q mean	Q Max	Date(*Q Max*)	Q Min	Date(*Q Min*)	%VD$_{rs}$ Annual value	%VD$_{rs}$ Average on the period
Kandadji	1976/1977	975	2050	26/01/1977	9.3	05/07/1976	23.3	31.3
	1977/1978	590	1580	11/12/1977	8.5	31/05/1978	30.8	
	1978/1979	843	1830	28/12/1978	5.5	07/06/1978	31.0	
	1979/1980	875	1930	28/12/1979	8.3	09/07/1979	30.7	
	1980/1981	620	1500	10/12/1980	6.3	29/06/1980	31.6	
	1981/1982	743	1760	23/12/1981	4.7	22/06/1981	33.2	
	1982/1983	602	1470	09/12/1982	10.1	28/05/1983	38.3	
	2005/2006	818	1690	11/12/2005	42.0	13/05/2006	41.2	35.0
	2006/2007	854	1730	26/12/2006	43.0	21/06/2006	33.9	
	2007/2008	787	1790	31/12/2007	30.6	25/06/2007	30.0	
	1975-2008	*721*	*2100*	*13/01/1976*	*1.1*	*07/07/1985*	*N/A*	
Niamey	1976/1977	925	1930	24/01/1977	14.0	28/06/1976	24.4	33.0
	1977/1978	566	1400	13/12/1977	7.0	28/05/1978	33.5	
	1978/1979	833	1800	08/01/1979	6.0	05/06/1978	31.5	
	1979/1980	909	1950	01/01/1980	8.41	29/05/1980	31.8	
	1980/1981	659	1500	09/12/1980	3.89	28/06/1980	35.3	
	1981/1982	748	1730	22/12/1981	2.62	28/06/1981	33.6	
	1982/1983	614	1390	11/12/1982	3.91	15/06/1982	40.9	
	2005/2006	902	1730	03/09/2005	47.8	28/05/2006	45.2	40.5
	2006/2007	925	1840	30/08/2006	33.2	03/07/2006	38.2	
	2007/2008	945	1830	01/01/2008	34.0	25/05/2008	38.1	
	1929-2008	*879*	*2360*	*30/01/1970*	*0.0*	*03/07/1974 and 15/06/1985*	*N/A*	

%VD$_{rs.}$= volume of water discharged between June and October as a percentage of annual volume discharged

With respect to the long-term mean discharge, the measurement campaign carried out between 1976 and 1982 occurred during a relatively variable period of high river discharge and low river discharge. The measurements for the present study 2005-2008 were carried out during a period with higher mean daily discharge than the long-term average. In the period between 1976 and 1982 peak discharges at Kandadji and Niamey were close to the long term maximum discharge for the station and minimum discharge values were relatively low. Between 2005 and 2008, peak discharge was considerably lower than the long-term value and minimum discharge was much higher than the 1976 to 1982 period.

The major difference between the two representative stations is that while at Kandadji the peak discharge occurred at about the same time for all the years under consideration, at Niamey it occurred much earlier in 2005 and 2006. In order to estimate the influence of the local rainy season on river discharge, the volume of water discharged during the rainy season (June to October) as a percentage of the total annual volume discharged is represented as $\%VD_{rs}$.

In general, at the Niamey station, the discharge volume that occurred in the rainy season as a percentage of total annual discharge volume is markedly higher for the 2005 to 2008 period in comparison to the 1976 to 1982 period.

3. Conclusions

The following conclusions can be drawn at the end of this part of the study:

- The hydrological analysis of the middle Niger River shows that:
  - River discharge is largely dependent on precipitation and the effect of reduced precipitation on river discharge. The role of base flow in sustaining low flows of the middle Niger River has been demonstrated.
  - The average hydrograph of the middle Niger River has two crests: a first peak with a steep rising limb that occurs during the local rainy season, and a second peak that occurs because of the discharge from of the inner delta's storage. The first peak discharge is more prominent around Niamey and is less prominent further upstream or downstream of Niamey.
  - The tributaries of the middle Niger River have not responded in the same way as the Niger River. The cumulative volume discharged at Niamey is increasing relative to Kandadji, a trend that cannot be explained as being solely due to the increase in discharge of gauged tributaries, the discharge of ungauged intermittent streams is also increasing. A study of these ungauged intermittent streams may provide a better understanding of this phenomenon assuming that losses from evaporation, infiltration, and abstraction did not reduce between 1998 and 2008.
  - The present study was carried out during a relatively homogenous period of increasing local runoff contribution to the Niger River's peak flows.

- Simulation of river discharge using the CARIMA model of the Niger River gives results in good agreement with measured values but may need to be verified against a station of known discharge to be accepted as reliable.

Part V - Sediment transport in the middle Niger River basin

An understanding of the sediment transport dynamics of the middle Niger River is vital because apart from having an adverse effect on water quality and the aquatic habitat, sediment deposits can also fill up hydraulic works along the river. A better understanding of the sediment transport of the middle Niger River is particularly important for basin management in view of the reducing river discharge.

In comparison to hydraulic or hydrological studies, sediment transport studies in general require more data but usually give less precise results. The main information that this part of the study aims to derive is essentially that on erosion and deposition trends along the middle Niger River.

In order to achieve this aim it was necessary to:

- Set up an appropriate sediment-sampling program to measure the concentration of suspended sediment along the middle Niger River and some of its tributaries in order to quantify the sediment transported in the study area;
- Analyse the size characteristics of the riverbed material found in the middle Niger River and some of its tributaries;
- Analyse the size characteristics of sediment transported in suspension by the middle Niger River and some of its tributaries;
- Calculate the sediment transport capacity at different points along the middle Niger River from measured and simulated hydrodynamic data.

1. Methodology

The measurement of sediment discharge can be complex because it is made up of two components, one component is transported either in suspension by flowing water while the other component is transported along the streambed. In suspension, sediment transport is measured as suspended sediment concentration (SSC) being the quantity of sediment transported per unit volume of water, while bed load transport is the quantity of sediment transported per unit time along the riverbed.

The suspended sediment component of the total sediment discharge is of particular interest when basin erosion is to be estimated, as is the case in this study. This is because transport by suspension is the likely mode of transport of eroded sediment from the river basin and thus can be considered as a surrogate measure of basin erosion.

1.1. Suspended sediment measurement methods

The numerous methods that exist for the estimation of suspended sediment concentration can generally be divided into direct and indirect measurement methods.

- **Direct methods:** Direct measurements of SSC consist of trapping a given quantity of the water-sediment mixture. The simplest form of direct sampling involves dipping a bottle or bucket into the watercourse and extracting the required sample. Vacuum action can also be used to extract a sample directly as used in pump samplers but due to the pumping action pump samplers rarely sample iso-kinetically.

  Depth integrating samplers and point integrating samplers can be described as sophisticated bottle samplers, in that they are designed to automatically take composite samples over a given vertical or at different points on a cross-section.

- **Indirect methods**: Indirect measurements aim to simplify the sampling task through a surrogate parameter that can be related to measured concentration values.

  Baban [1995], Gomez et al. [1995] and Nellis et al. [1998] applied a remote sensing method where reflectance values of water are related to ground referenced values of suspended sediment concentration. Acoustic methods have also been used to estimate SSC; SSC is estimated as the acoustic intensity of backscattering signals due to particles suspended in the stream flow [*R L Dinehart and J R Burau*, 2005; *P D Thorne et al.*, 1993]. Optical methods that estimate SSC by relating stream turbidity measurements to measured SSC are also common [*I D L Foster et al.*, 1992]. The use of indirect measurement methods is advantageous because they can be time- and labour-saving but their major drawback may be the fact that the results obtained using these methods are only as good as the directly measured data used for the calibration of the measurement equipment.

Wren et al.[2000] noted that although there are various methods for the estimation of SSC, bottle samplers remain the standard by which other sampling methods are calibrated.

The purpose and objectives of a study are the most pertinent factors in choosing an appropriate method for the measurement of SSC.

Other factors that influence the choice of sampling methods for SSC determination include but are not limited to the size of the sampling area, the appropriate sampling interval, the sediment size fraction(s) of interest, operational ease, as well as cost. Wren et al. [2000] describe methods for the measurement of suspended sediment concentration as well as their advantages and disadvantages.

1.2. Method applied in this study

Burkham [1985] posited that increasing sampling frequency increases data accuracy up to a maximum level at which point deviations from true values can be said to represent random errors due to turbulent fluctuations in the water-sediment mixture and random systematic errors due to instrumentation, sampling technique and computation.

Data quality is only limited by the cost of equipment for field and laboratory measurements for near continuous sampling. Daily sampling was adopted in order to increase the accuracy of suspended sediment discharge data, with respect to earlier sampling (see paragraph 2.1) on the Niger River that employed a three-day sampling interval.

The daily grab samples were taken from each of the sampling stations by lowering a one-litre bottle to at least 50 cm below the water surface and allowing it to fill up. Rooseboom and Annandale [1981] compared a large databank of sediment samples obtained in this way to average concentrations obtained from more sophisticated optical methods. They found that results obtained by the "bottle method" were generally about 25% lower than those obtained using methods that are more sophisticated.

2. Measuring stations and data

The stations at which measurements were made are presented in the following paragraphs with an overview of existing river sediment data for the study area.

2.1. Previous work in the middle Niger basin

Direct monitoring of the SSC for the middle Niger River and its tributaries is rare and has hardly been carried out at more than one station in a downstream sequence for the same period of observation.

Between 1976 and 1983, SSC was measured on the Niger River at Kandadji and on the Gorouol River at Dolbel by ORSTOM [*R Gallaire*, 1986; *R Gallaire and R Gathelier*, 1982; *R Gallaire et al.*, 1981; *R Gallaire et al.*, 1982; *P Harang and R Gathelier*, 1979; *M Hoepffner*, 1978].

SSC measurements were also carried out on the Niger River at Niamey from 1984 to 1986 [*R Gallaire*, 1995]. The data for Niamey was only available as monthly sediment flux. The duration and frequency of these earlier sediment-monitoring programs are presented in Table V- 1 and the sampling locations are shown in Figure V- 1.

Table V- 1: Summary of available historic sediment data for the middle Niger basin

River	Station	Period	Sampling frequency
Niger	Kandadji	July 1976 - May 1983	~ 3 day interval
Niger	Niamey	February 1984 –September 1986	~ 3 day interval
Gorouol	Dolbel	June 1976 - October 1982	~ 3 day interval

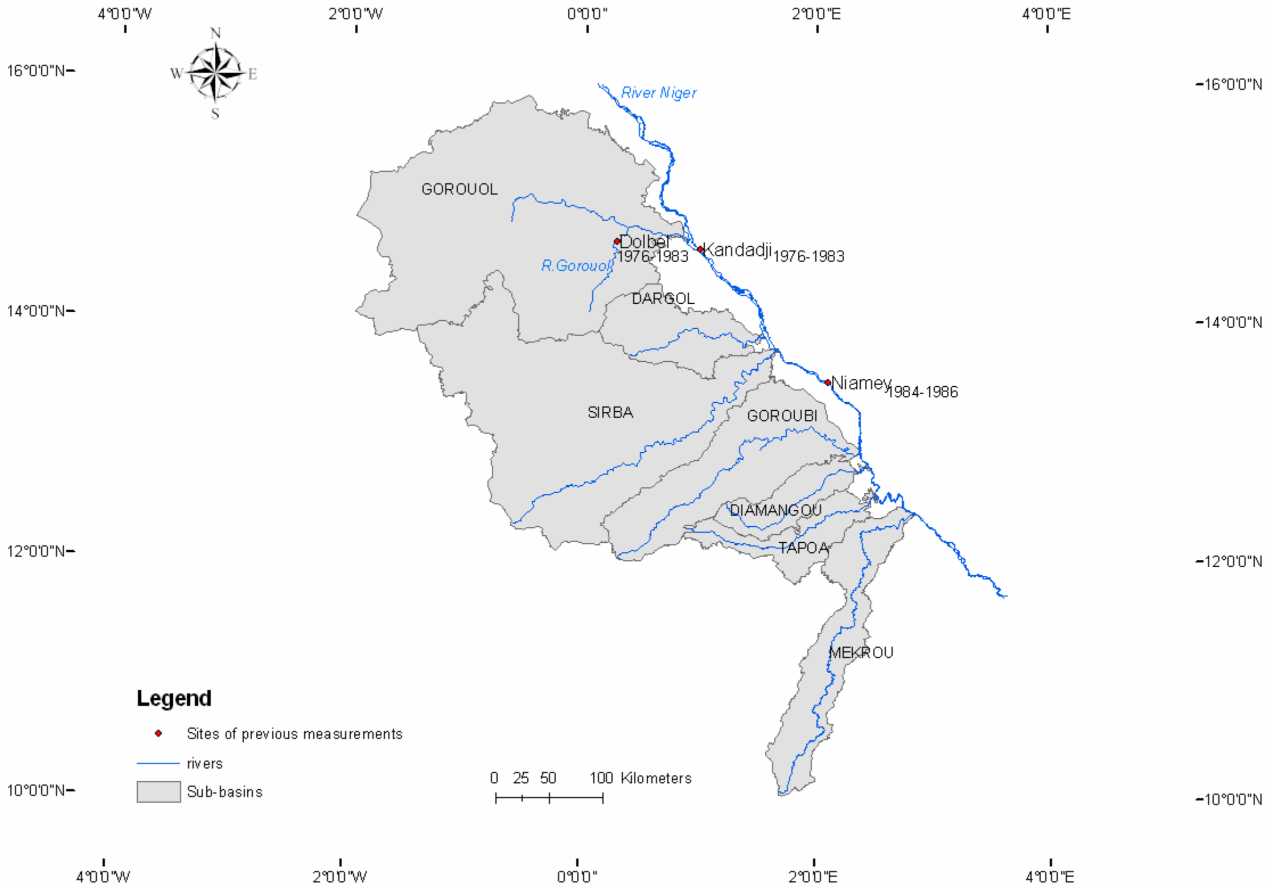


Figure V- 1: Locations of previous suspended sediment measurements

2.2. Choice of measuring stations for the present study

Because one of the main objectives of the present study was to measure the sediment flux along the middle Niger River and its tributaries, the measuring stations for this study were sited to locate them:

- near a zone of degradation (of vegetation and/or soil) or deposition of alluvium (as identified from satellite imagery);
- at or near river flow gauging station in order to measure the corresponding water discharge for measured sediment concentration values;
- in relatively accessible areas.

Two sub-basins were chosen in the semi-arid Sahelian zone (the Gorouol and the Sirba), while the Mékrou in the Sudan zone was chosen in order to compare the sediment flux along the Niger crossing the two zones and to provide a representative set of sampling points with respect to the middle Niger River.

At the confluence of all three tributaries with the Niger, two measurement stations were chosen, one upstream and one downstream, in order to study sediment transfer from the tributaries to the Niger.

Measurements were also carried out on the tributaries of the Niger River in order to quantify the sediment transport of the tributaries and transfer to the River Niger. On the Gorouol, measurements were made at Alcongui, while the sediment transport from the Sirba was measured at two stations on the Sirba (at Tiambi and at Garbé- Kourou).

The Gorouol and Sirba are representative Sahelian basins and were chosen because of vegetation and soil degradation of their basins evaluated in part III as well as for their relatively large catchment areas in comparison to the other tributaries of the middle Niger River. Although no sampling was carried out on the Mékrou River itself due to reasons of accessibility, stations upstream and downstream of its confluence with the Niger River were selected in order to contrast the sediment input of Sahelian rivers with the input of a river basin with more rainfall and vegetation cover.

Overall, the measuring stations were located in stable cross-sections and in straight reaches free from backwater effects. The sampling stations for this study are located in the study area as shown in Figure V- 2.

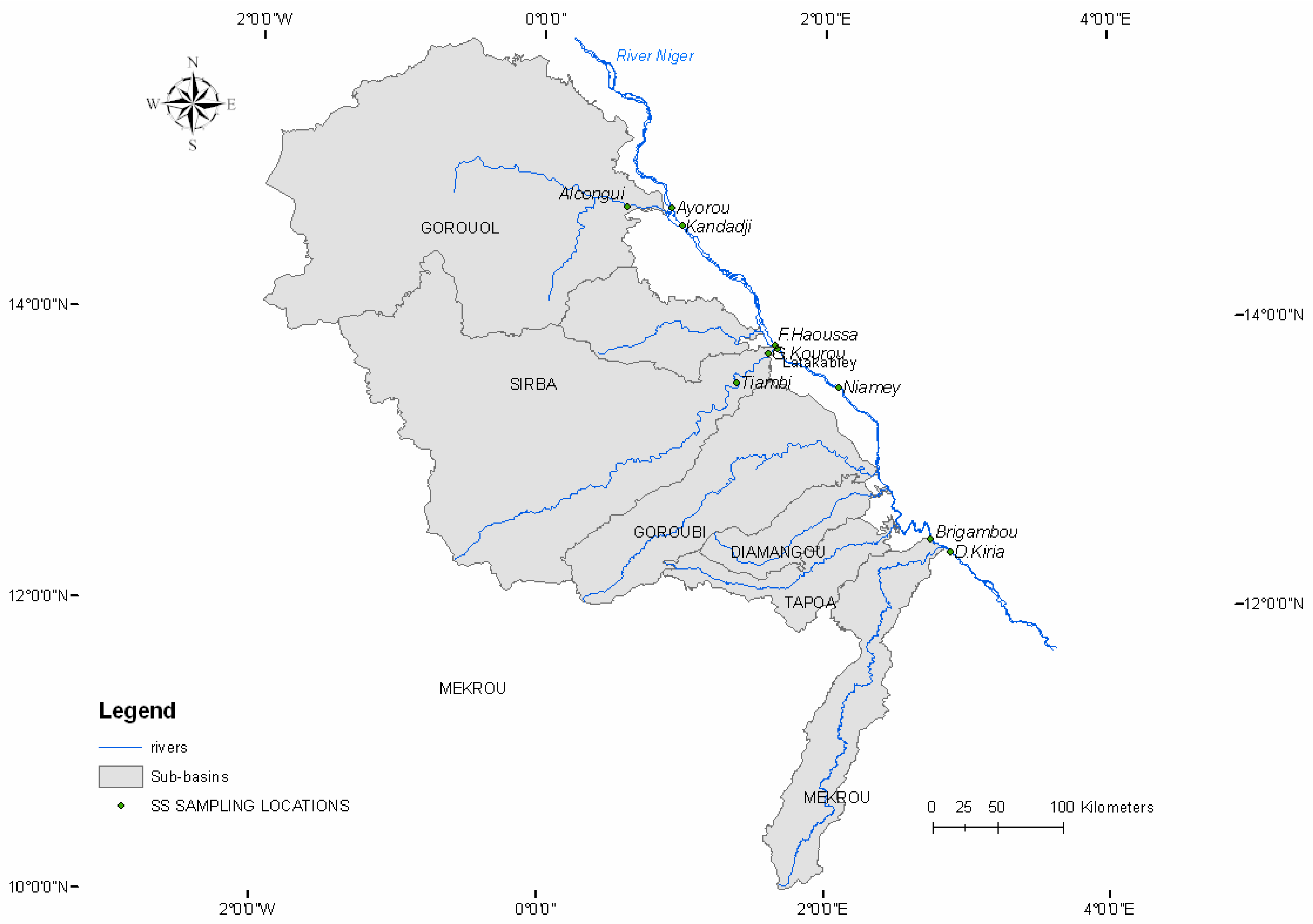


Figure V- 2: Sampling stations for suspended sediment

3. Suspended sediment analysis

The fate of river sediment depends on the sediment size composition in addition to sediment supply. The size of sediment particles is an important sediment property that along with flow conditions determines the sediment transport processes like entrainment, transport, and deposition.

Sediment grain size analysis can therefore provide information about the sediment source, transport history as well as deposition conditions [*S J Blott and K Pye*, 2001].

3.1. Laboratory determination of the suspended sediment concentration of a river water sample

Two laboratory methods were applied for the determination of suspended sediment concentration in conformity with the ASTM International's "Standard Test Methods for Determining Sediment Concentration in Water Samples"[*ASTM Standard D 3977-1997*, 2007]:

- Evaporation (Test method A): The evaporation method described in sections 8 to 13 of ASTM standard D 3977-97 was employed for the determination of the suspended sediment concentration of the river water samples.
- Filtration (Test method B): The filtration method described in sections 14 to 19 of ASTM standard D 3977-97 was also used to determine the suspended sediment concentration of the river water samples. This was particularly necessary considering the fact that with the evaporation method samples required a storage time of about 10 to 14 days to settle before the analysis by evaporation. The samples were filtered through Whatman 934-AH, glass micro-fibre filters with 1.5µm particle retention. The filtration method allowed a same-day analysis on the samples.

Over 90% of the samples were analysed by the evaporation method while the filtration method was mostly applied to get a first estimation of SSC values for control samples and to check control the quality of the results obtained by the evaporation method that was carried out on a large scale.

The precision and bias data given by ASTM [2007] indicate that the evaporation method is more accurate than the filtration method for low suspended sediment concentrations of about 10 mg/l. The results obtainable by the two methods are very similar at concentrations around 1000 mg/l.

3.2. Deriving suspended sediment concentration values for a cross-section

A large part of sampling error for direct sampling methods probably occurs in obtaining the water-sediment sample from the stream. The errors are largely due to the variability in the concentration of sand-sized sediment particles. Representative sampling becomes particularly difficult in streams with a large concentration of sand-sized sediment.

Picouet [1999] observed a strong linear relationship between single grab samples and multi-vertical samples in the "Upper Niger River", which is upstream of the present study area. This indicates that the suspended sediment concentration can be expected to vary only slightly in the vertical direction. However, in large rivers like the Niger, suspended sediment concentration may vary across the river section. In order to account for cross-sectional suspended sediment concentration variability, it was necessary to estimate a mean cross-sectional value[5] of suspended sediment concentration "SSC_X". The single grab samples were calibrated to a few measured cross-sectional values along the Niger River from Ayorou to Diabou-Kiria (see Figure V- 2).

Suspended sediment concentration was sampled at a minimum of three verticals at three depths at the time of obtaining the usual single grab sample several times during the measurement period. The relationship obtained between the suspended sediment concentrations of the single grab samples and the measured cross-sectional values is presented in Figure V- 3.

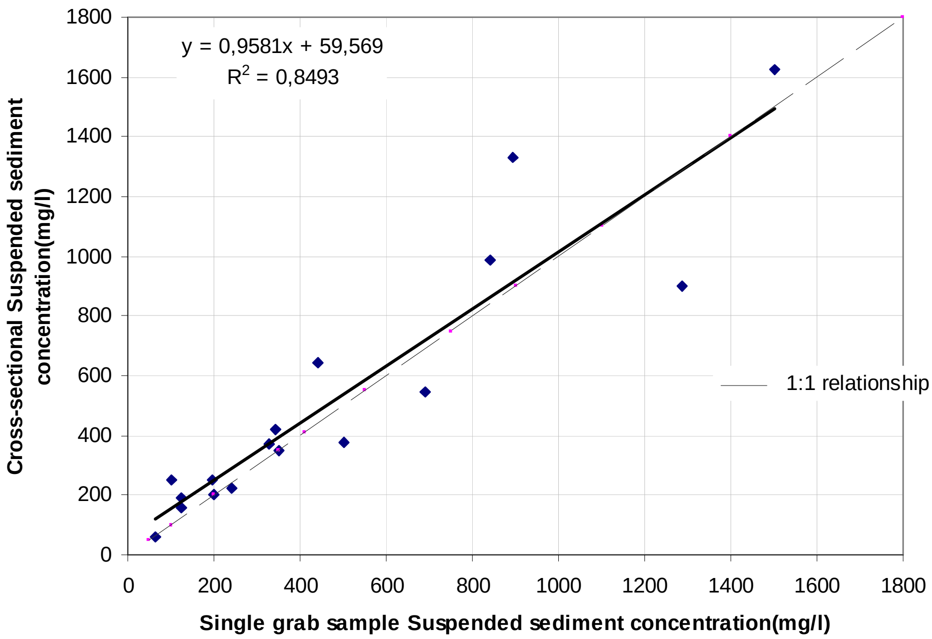


Figure V- 3: Relationship between sampled cross-sectional SSC (n=16) and single sample SSC for the middle Niger River 2007

[5] The mean suspended sediment concentration of a minimum of three verticals per cross-section

At the Niamey station, up to ten verticals were sampled from the Kennedy Bridge.

The relationship obtained was then used to estimate the mean cross-sectional suspended sediment concentration values SSCx given in equation V-1.

$$SSC_X = 0.9581(SSC) + 59.569$$ **Equation V- 1**

$$r^2 = 0.8493; n = 16$$

Where SSC_x= estimated cross-sectional suspended sediment concentration; SSC= suspended sediment concentration of a single grab sample; n= sample size.

At values above about 1000 mg/l, Equation V- 1 (the solid line in Figure V- 3) is convergent with the 1:1 line, suggesting that at values above 1000 mg/l, the suspended sediment concentrations obtained from single grab samples are representative of the mean cross-sectional values and do not vary considerably. At low suspended sediment concentrations, the single grab sample underestimates the mean cross-sectional suspended sediment concentration by up to 60 mg/l (i.e. up to 45% at the lowest measured concentrations).

3.3. Determination of sediment grain size

Due to the wide range of sediment particle characteristics, the appropriate method for the determination of sediment grain size is usually dependent upon the size characteristics of the sediment particles. For example, due to their large sizes, material such as boulders and cobbles are measured directly by circumference or diameter. Intermediate sizes, ranging from gravels to sands, are measured semi-directly by sieves while small sizes ranging from sands to clay are measured by sedimentation (i.e. their settling characteristics in water) or by laser diffraction (i.e. their diffraction of light).

In addition to suspended sediment sampling, bed material was also collected at each of the suspended sediment sampling stations. The difference in the mode of collection, the quantity collected as well as the particle sizes of the two types of samples made it necessary to apply different methods for the determination of the sediment particle size of the samples.

The grain size distribution for bed material samples was determined by the sieve analysis of bulk samples (usually gravel size or smaller) or pebble count (coarse gravels and cobbles), while the size distribution for suspended sediment was determined by laser diffraction.

Table V- 2 shows a Wentworth classification of sediment particle size [modified from Kondolf et al.[2003]].

Table V- 2: Sediment size classification

Designation	Sub-designation	Size limits(mm)
Boulder	Boulder	> 256
Cobbles	Large Cobbles	128 – 256
	Small Cobbles	64 – 128
Gravel	Very coarse Gravel	32 – 64
	Coarse Gravel	16 – 32
	Medium Gravel	8 – 16
	Fine Gravel	4 – 8
	Very fine Gravel	2 – 4
Sand	Very coarse Sand	1 – 2
	Coarse Sand	0.5 – 1
	Medium Sand	0.25 – 0.5
	Fine Sand	0.125 – 0.25
	Very fine Sand	0.0625 – 0.125
Silt	Coarse Silt	0.0312 – 0.0625
	Medium Silt	0.0156 – 0.0312
	Fine Silt	0.0078 – 0.0156
	Very fine Silt	0.0039 – 0.0078
Clay	Coarse Clay	0.002 – 0.0039
	Medium Clay	0.001 – 0.002
	Fine Clay	< 0.001

3.3.1. Pebble count

Due to the variable nature of the Sirba river bed at Garbe Kourou two methods had to be used : the Wolman pebble count method [*M G Wolman*, 1954] was employed in the characterization of the sediment particle size in the coarse gravel sector and bulk sampling in the sand sector. One hundred particles were randomly sampled from the riverbed surface.

3.3.2. Sieve Analysis

Sediment samples from the river bottom were oven-dried at 105°C, weighed on a balance with an accuracy of 0.1g and sieved through a column of sieves with openings of 10, 5, 2.5, 1.6, 0.63, 0.315, 0.2, 0.125, 0.1, 0.08, 0.063, and 0.05 mm respectively. The sieving action was facilitated by a mechanical sieve shaker for about 15 minutes. Each sediment sample weighed a minimum of 100 g.

3.3.3. Particle sizing by laser diffraction

The particle size of sediment in suspension was determined by the laser diffraction method. The residues obtained from the evaporation method in 3.2.1 were used to determine the suspended sediment particle size. The laser diffraction technique is based on the principle that particles passing through a laser beam scatter light at an angle directly related to their size. The Malvern Mastersizer 2000, with a measurement size range of 0.02- 2000 μm was used for this test.

4. An overview of previous studies

The results obtained in the present study are detailed after a brief discussion of the results obtained in previous suspended sediment measurement campaigns, and in particular the data obtained by ORSTOM for the middle Niger River basin [Gallaire, 1986].

The results of the measurements carried out by ORSTOM [R *Gallaire*, 1986] between 1976 and 1985 are discussed because they represent the only measured sediment data for the middle Niger River basin (the Gorouol at Dolbel and the Niger River at Kandadji and Niamey) and can thus serve as a baseline to which the present study can be compared.

Data from the Upper Niger River and interior delta [*C Picouet*, 1999] is also briefly discussed in comparison with data from the middle Niger River.

4.1. The Gorouol River

SSC measurements on the Gorouol River were carried out from 1976/77 to 1982/83 not at Alcongui but at Dolbel upstream of Alcongui (see Figure V- 4).

The SSC values measured at Dolbel can be expected to be close to values at Alcongui, given that the hydrographs at the two stations are of similar form and magnitude for the period and the Dolbel is located on the major branch of the Gorouol River.

Figure V- 4: The Gorouol basin

The suspended sediment concentration (SSC) ranged from 166.5 mg/l to 3820 mg/l at Dolbel on the Gorouol River (see Figure V- 5) over the seven-year period between 1976 and 1982.

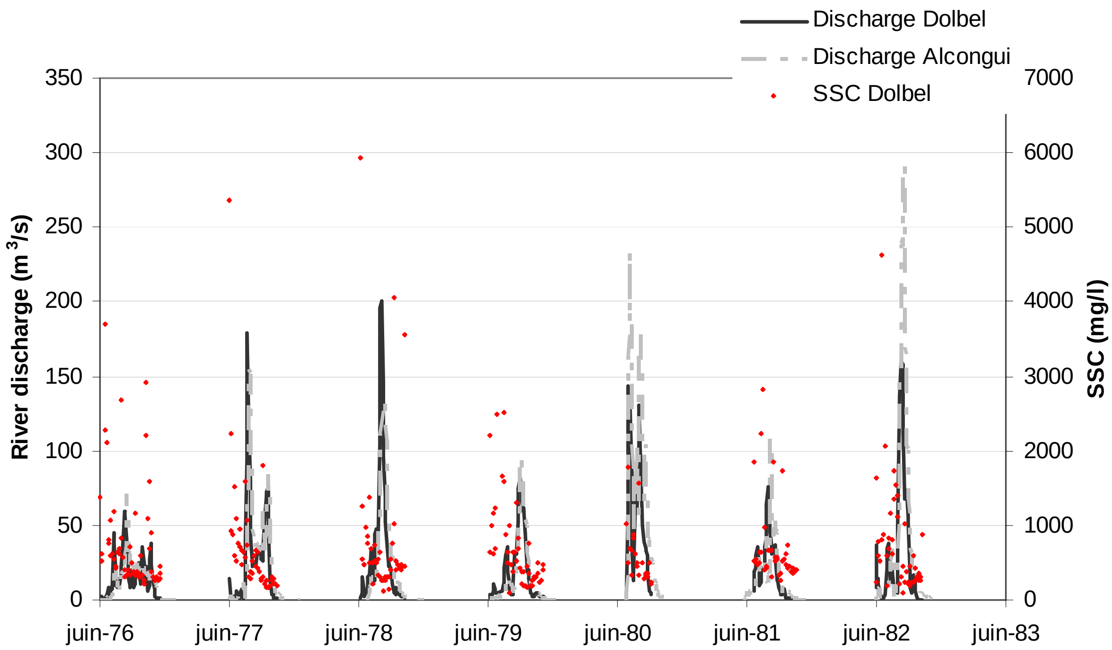


Figure V- 5: Discharge and SSC for the River Gorouol at Dolbel 1976 – 1982 [Source: Gallaire (1986)]

The calculated sediment flux of the Gorouol River at Dolbel for the period is presented in Table V- 3 using data from Gallaire [1986].

Table V- 3: Sediment flux of the Gorouol River at Dolbel

Period	River Discharge($10^6 m^3$/year)	Sediment flux (10^6 Tonnes/year)
1976/77	230.04	0.164
1977/78	334.16	0.173
1978/79	361.88	0.147
1979/80	249.42	0.155
1980/81	347.61	0.213
1981/82	204.05	0.147
1982/83	355.17	0.159

4.2. The Niger River

According to Picouet [1999], SSC data from the upper Niger River and its interior delta for the period between 1991 and 1998 indicated relatively low SSC values. SSC ranged from 0.1 mg/l to 45 mg/l between Banankoro and Ké-Macina (for the Upper Niger River) and from 4 mg/l to 250 mg/l between Akka and Diré for the Niger's interior delta. (See Figure V- 6 for the relative locations of the measuring stations).

A classic example of the SSC peaks preceding the river discharge peaks can be seen in Figure V-5 and Figure V-7.

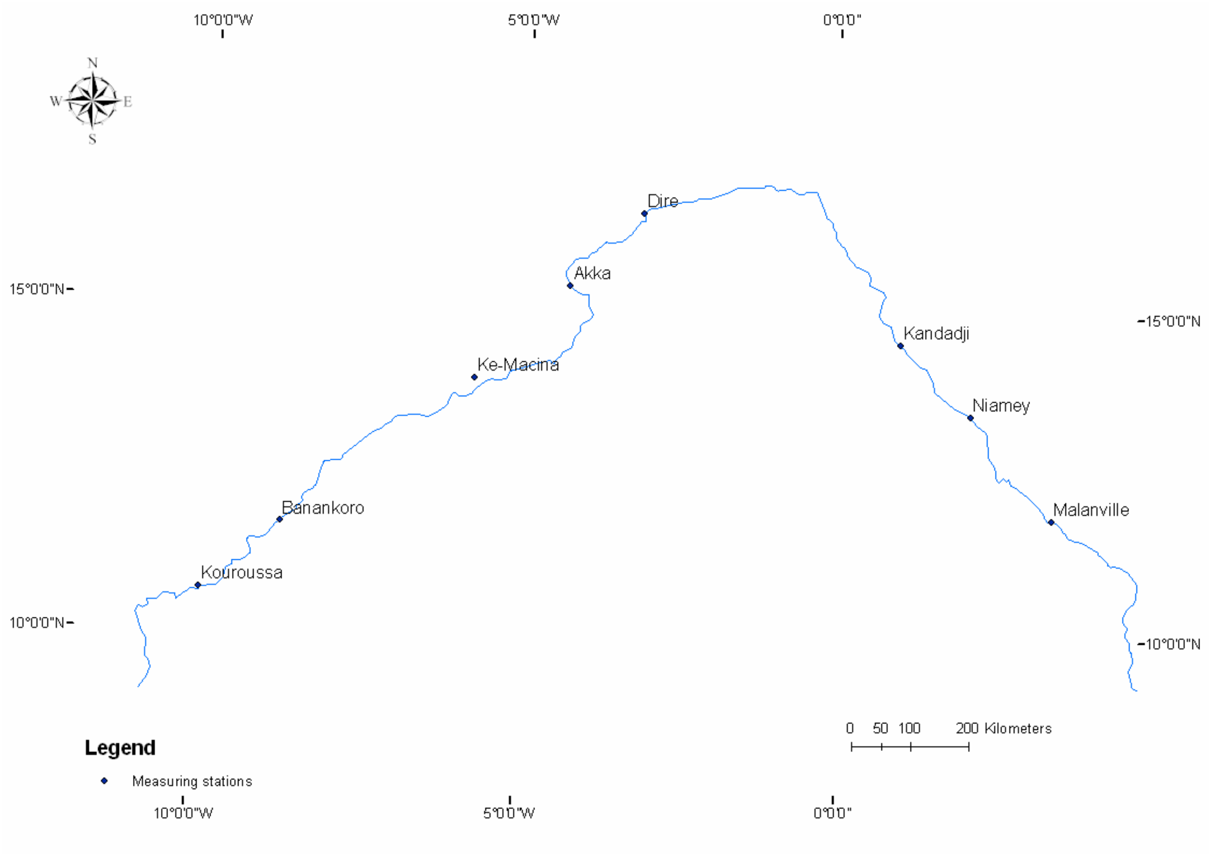


Figure V- 6: Measuring stations along the Niger River

Mean annual sediment flux ranged from 567,000 tonnes to 1.297 million tonnes along the upper Niger River between Banankoro and Ké-Macina and in the interior delta between Akka and Diré from 833,000 to 1.012 million tonnes.

When compared with the suspended sediment data from the upper Niger River the data acquired during the ORSTOM suspended sediment sampling program for Kandadji between 1976 and 1983 [R *Gallaire*, 1986] are much higher in terms of sediment concentration and sediment discharge. The SSC values at Kandadji ranged from 2 mg/l to 1600 mg/l between 1976 and 1982 (see Figure V- 7). The higher sediment concentration values observed in the middle Niger when compared to the Upper Niger may be due to the reduction in vegetation cover as the river flows from the Guinea Savanna to the drier Sahelian region. A second explanation for this increase in sediment concentration between the upper Niger and the middle Niger may be the Niger's "interior delta" from where stored sediment may be re-mobilized towards the middle Niger River.

The sediment flux calculated for the period using data from Gallaire [1986] is presented in Table V- 4 for the Niger River Kandadji and Niamey.

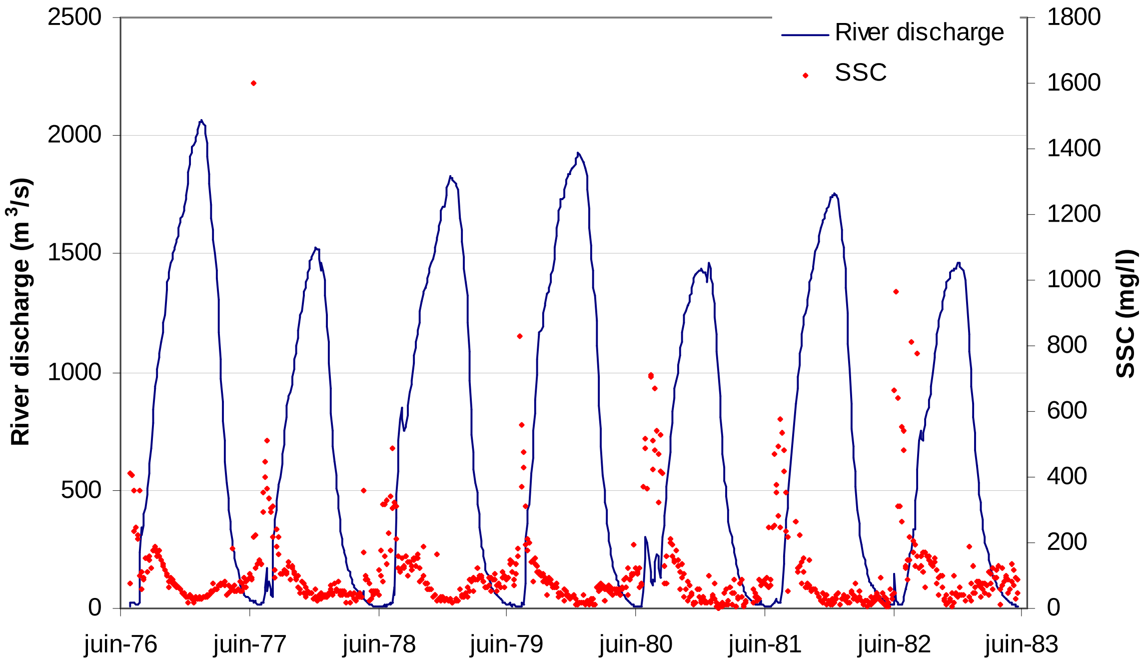


Figure V- 7: Discharge and SSC for the River Niger at Kandadji (1976-1982) [source: *Gallaire (1986)*]

Table V- 4: Sediment flux of the middle Niger River at Kandadji and Niamey

Station	Period	River Discharge($10^9 m^3$/year)	Sediment flux (10^6 Tonnes/year)
Kandadji	1976/77	30.073	2.007
	1977/78	18.090	1.287
	1978/79	26.580	1.831
	1979/80	27.669	1.469
	1980/81	18.990	1.485
	1981/82	23.424	1.528
	1982/83	19.004	1.680
Niamey	1984/85	13.015	3.162
	1985/86	19.146	3.919

4.3. Discussion of the methods and results of the previous study

The primary sources of discrepancy between any two distinct sediment-sampling programmes are sampling method and frequency. The ORSTOM sampling program for the middle Niger River employed a similar water-sediment sample extraction method as the present study. The major differences in the two measurement programmes were:

- Sampling frequency: While daily measurement was adopted in the present study, SSC data for the previous study were obtained at 3-day intervals.
- Laboratory equipment: The composition of sediment samples is critical in choosing the method for determining the concentration of a water-sediment sample.

The ORSTOM sampling program on the middle Niger River employed the filtration method to determine SSC values using 10 μm size filters. Gallaire [1995], citing work by Esteves and Taupin between November 1992 and April 1993, estimated that the sediment particles smaller than 10 μm, which may have been excluded by the filter size, were of the order of 10 to 15 % of the total suspended sediment volume.

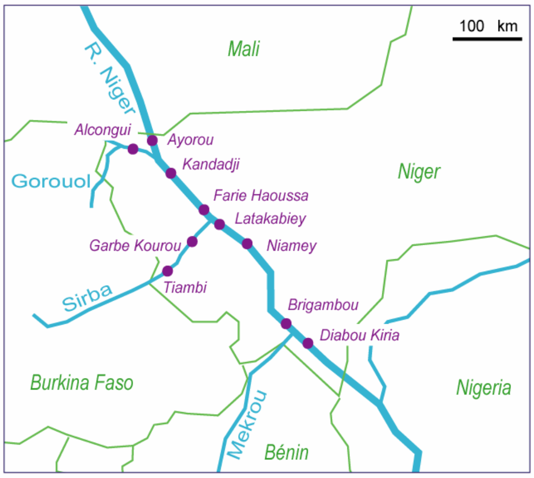
An analysis of about 360 sediment samples obtained throughout the hydrological year at Kandadji and Niamey between 2006 and 2008 indicated that on average, the percentage of sediment particles less than 10 μm was about 25%. This discrepancy in the percentage of particles less than 10 μm, could indicate a change in sediment source at Kandadji between the 1980s and the period of the present study or may be due to the paucity of data in the ORSTOM study used to determine grain size distribution of suspended sediment. A change in sediment source in this case would indicate higher basin erosion leading to higher SSC values.

The unmeasured sediment particles (<10 μm) alone, do not account for the large difference in calculated sediment fluxes. Burkham [1985] and Phillips et al.[1999] found that sampling interval exerts a significant influence on sediment flux estimates, with precision declining as sampling frequency was reduced. Phillips et al.[1999] working on the River Ouse in England found that the reference sediment load (measured at 15-minute intervals) was underestimated by between 108 and 22% by weekly sampling, by between 108 and 20% by fortnightly sampling and by between 110 and 13% by monthly sampling. Sampling frequency is particularly pertinent in the middle Niger River where SSC values show a high variability in the rainy season as will be shown in the following sections. A daily sampling interval was applied in the present study compared to the 3-day sampling employed in the previous study.in order to improve the measurement accuracy within the limits of this study.

Therefore, any attempts at a comparison between the previous measurements and the present study should consider the following points:

- With respect to the present study, the sediment concentration values previously obtained for the middle Niger basin may be up to 25% less than the values measurable by the present study.
- In terms of the calculation of sediment flux, the 3-day interval applied in the previous study would have introduced a greater degree of error in comparison to the daily sampling programme used for the present study.

5. Results from the present study



The results obtained for the present study are presented in the following sections for the Gorouol River at Alcongui, for the Sirba River at Tiambi and Garbé-Kourou and for the middle Niger River at Ayorou, Kandadji, Farié-Haoussa, Latakabiey, Niamey, Brigambou, and Diabou-Kiria.

The measured sediment characteristics of the study area are described in the following paragraphs. The SSC values are presented in relation to discharge at each of the stations. The SSC characteristics are further investigated in terms of sediment particle size classes for a majority of the suspended sediment samples. The suspended sediment transported at the sampling stations of the study area have been divided into five classes for the purposes of this study: 0-40 µm (clay to medium silt), 41-70 µm (coarse silt), 71-125 µm (very fine sand), 126-630 µm (fine to medium sand), 631-1600 µm (coarse to very coarse sand).

5.1. Results for the Gorouol River

5.1.1. Riverbed sediments

An analysis of the bed sediment at Alcongui in 2006 and 2007 showed that the riverbed is made up of fine to medium sand, with a median particle size of about 230 µm.

5.1.2. Suspended sediment concentrations and grain size

Suspended sediment concentration (SSC) ranged from 137 mg/l to 3060 mg/l in 2006/07 and from 124 mg/l to 3751 mg/l in 2007/08 at Alcongui station on the River Gorouol. These values are similar to the earlier measurements carried out on the Gorouol River at Dolbel.

SSC values of the Gorouol River at Alcongui are plotted alongside river discharge in Figure V- 8 for the 2006/07 and 2007/08 seasons. It can be noted that the magnitude of SSC values at Alcongui do not show a particularly strong dependence on river discharge but rather are related to the magnitude of rainfall at Alcongui. This is particularly true in July and August where SSC peaks occur around the same time as rainfall peaks (see Figure V- 9).

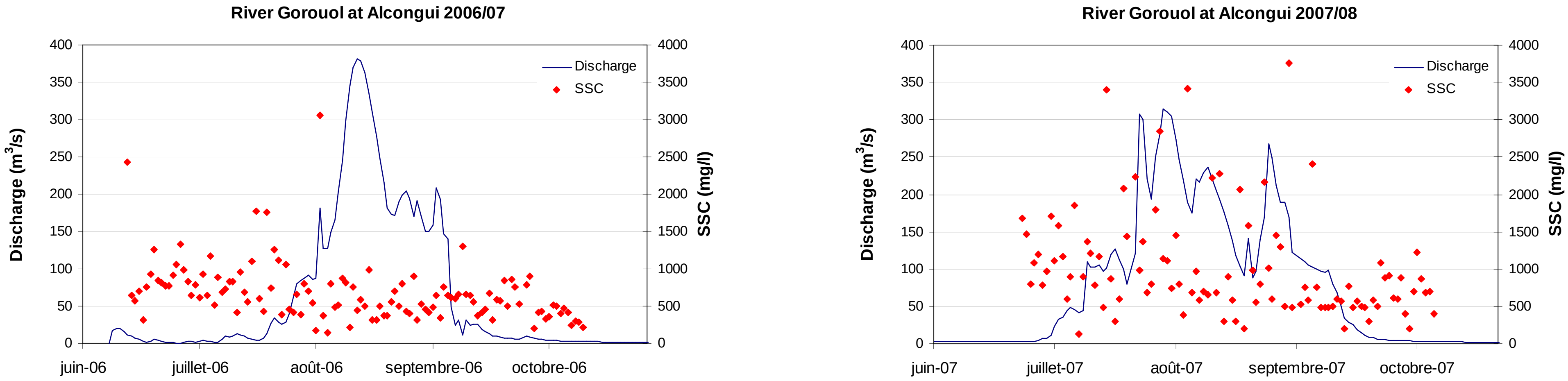


Figure V- 8: River discharge and SSC relationship for the River Gorouol at Alcongui (2006 and 2007)

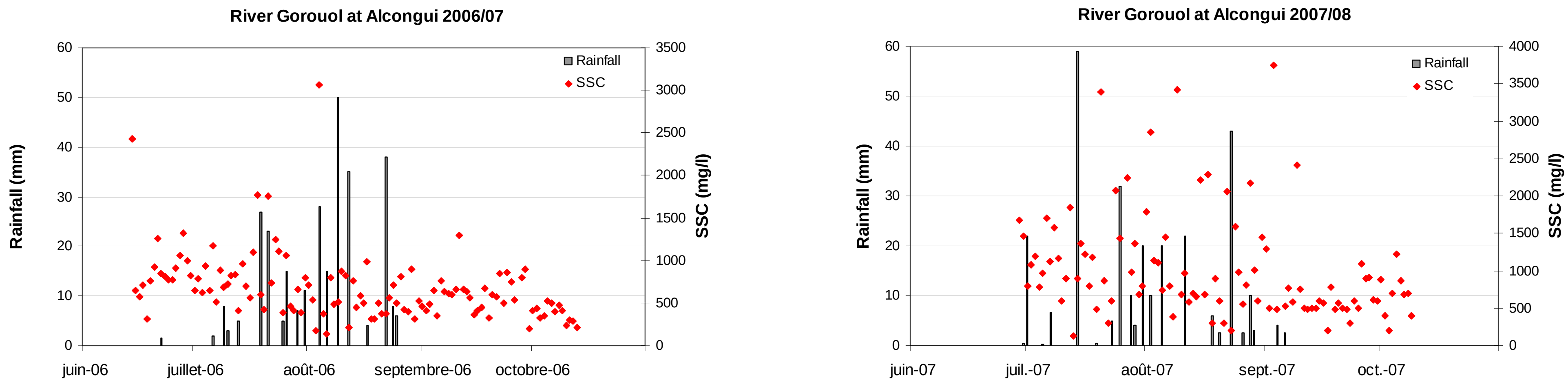
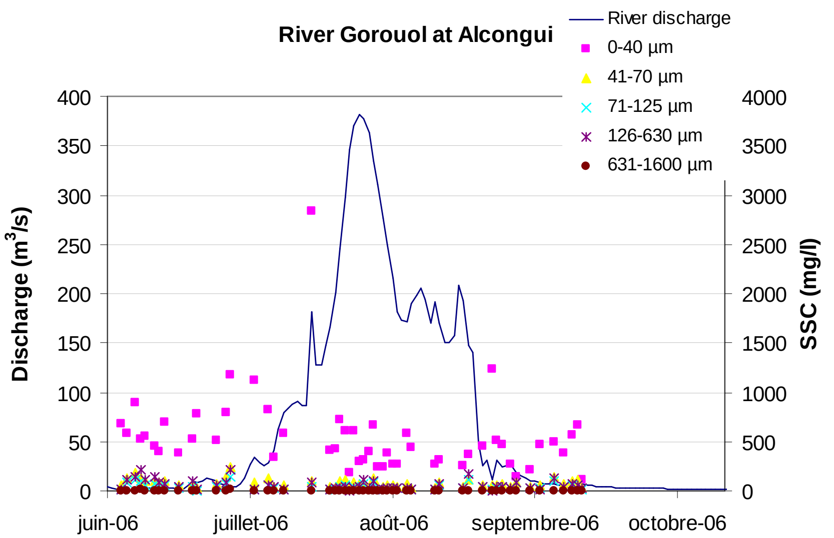


Figure V- 9: At-station rainfall and SSC relationship for the River Gorouol at Alcongui (2006 and 2007)

The concentration values of the sediment size classes present in suspension are presented with corresponding river discharge for the Gorouol River at Alcongui in Figure V- 10. It can be observed that the Gorouol River at Alcongui mainly transports sediment in the 0-40 μm size class. It can also be noted that the highest concentrations (up to about 200 mg/l) of coarse sediment particles (up to the 126-630 μm size class) are transported at the start of runoff.

The mean distribution of suspended sediment transported by the Gorouol River at Alcongui for the 2006/07 and 2007/08 seasons is presented in Figure V- 11. On average, during the study period, 74.5% of the suspended sediment transported by the Gorouol was clay and medium silt.



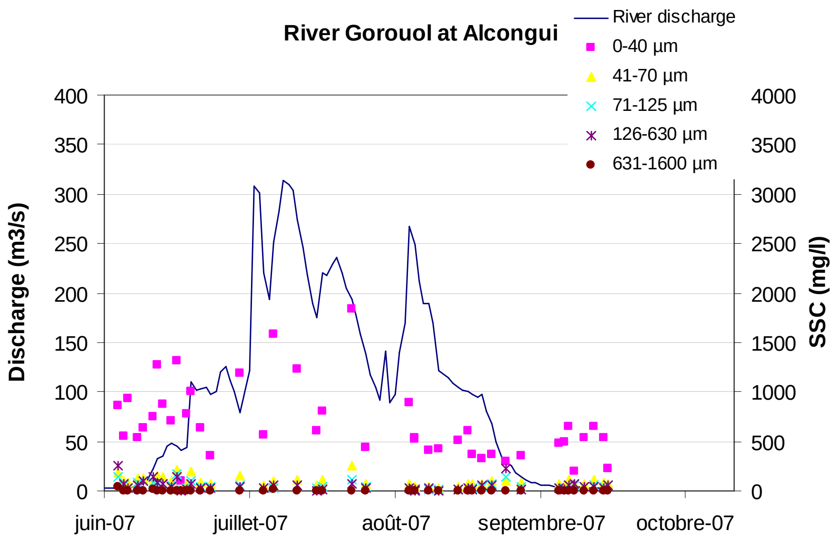


Figure V- 10: River discharge and SSC relationship for the River Gorouol (according to size class) at Alconguí (2006 and 2007)

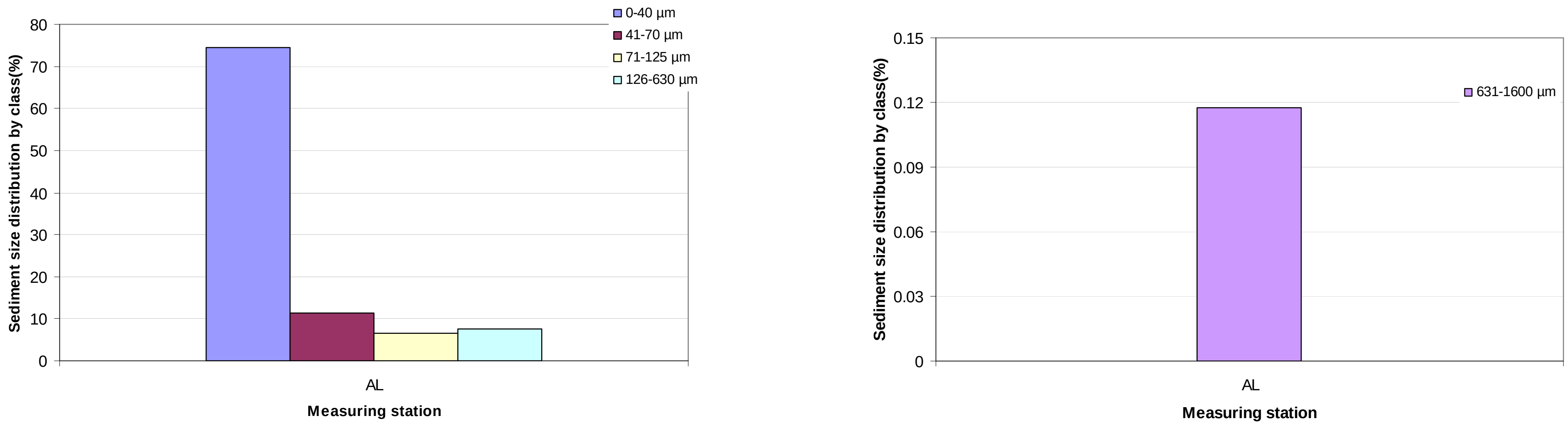


Figure V- 11 : Mean suspended sediment size distribution by percent transported by the River Gorouol at Alcongui (n=101 samples)

5.1.3. Changes in sediment particle size distribution

Figure V- 12 shows the variation of the percentage of sediment size particles (by class) in suspension with sediment concentration.

On average, the 0-40 µm particles represent over 70% of the volume of sediment transported in suspension by the Gorouol River at Alcongui. As sediment concentration increases the amount of very fine sediment, (0-40 µm) also increases. The figure also shows that the larger sediment particles (41-1600 µm) that are transported in suspension make up less than 35% at most of the total sediment transported in suspension. The coarser sediment groups make up a high percentage of total sediment only at low sediment concentration values. The Gorouol River at Alcongui rarely transports particle sizes greater than 630 µm.

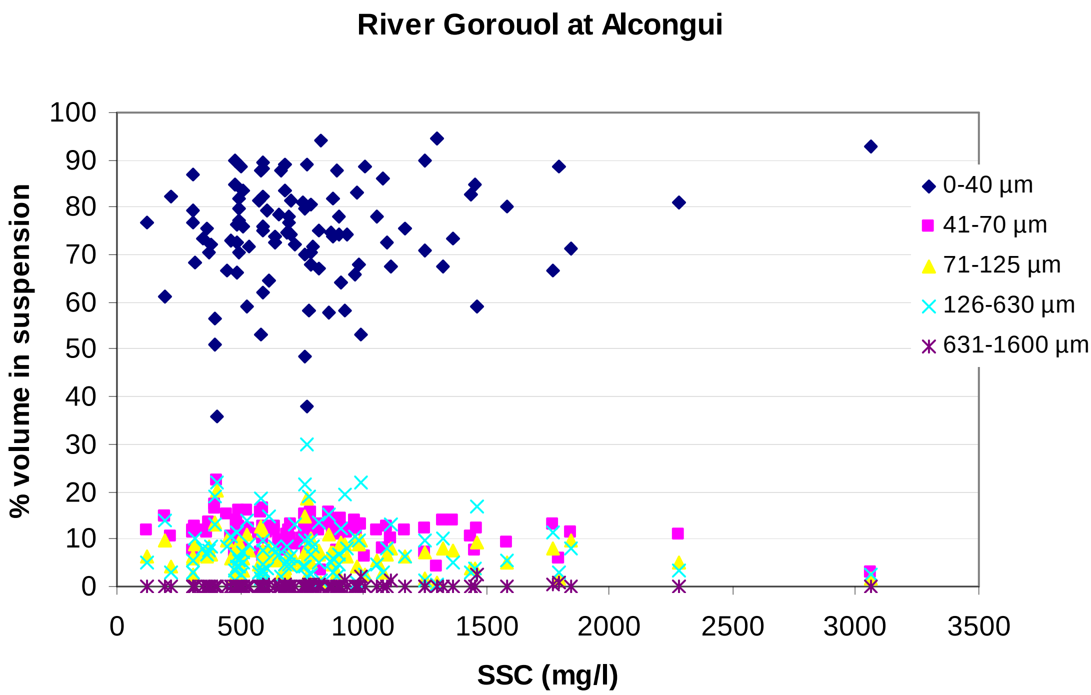


Figure V- 12: SSC and particle size data for the River Gorouol at Alcongui

The SSC and grain size observations for the Gorouol River at Alcongui can be summarized as schematized in Figure V- 14. At low SSC values, the suspended sediment consists of a mix of all sediment sizes. As SSC values increase, the 0-40 µm particles make up a much higher percentage of the sediment in suspension. This indicates that SSC peak values are largely due to basin erosion, occurring at the start of the rainy season and after the long dry season, transporting easily detachable sediment and aeolian sediment deposits.

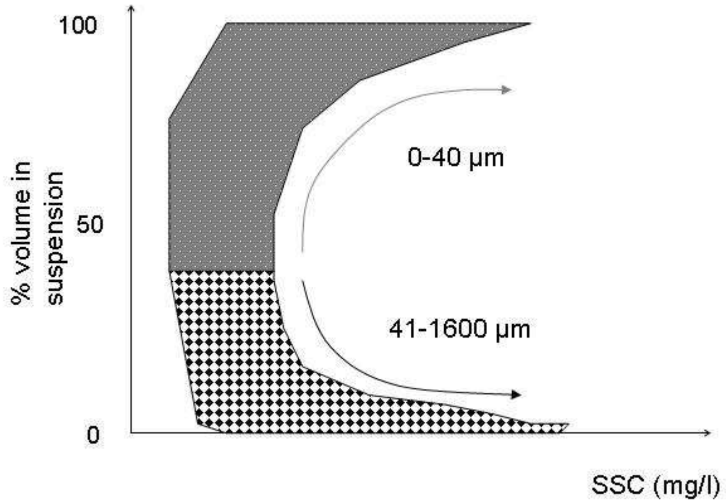


Figure V- 13: SSC and particle size relationship for the River Gorouol at Alcongui

The relationship of four of the suspended sediment size classes of with river discharge is described in Figure V- 14. In general, as rainfall linked river discharge increases, the 0-40 µm size in suspension increases up to a point where further increases in river discharge have no further effect on this size class. The percentage of coarser sediment in suspension shows a tendency to decrease with increasing discharge. This availability of very fine sediment, which may be entrained by raindrop impact and overland flow, appears to control the ability of the river flow to transport coarser particles. For this station, coarser sediment particles are mainly transported at the start of the rainy season, indicating that in addition to the fine sediment (0-40µm) transported, the Gorouol may also be transporting bed material in suspension.

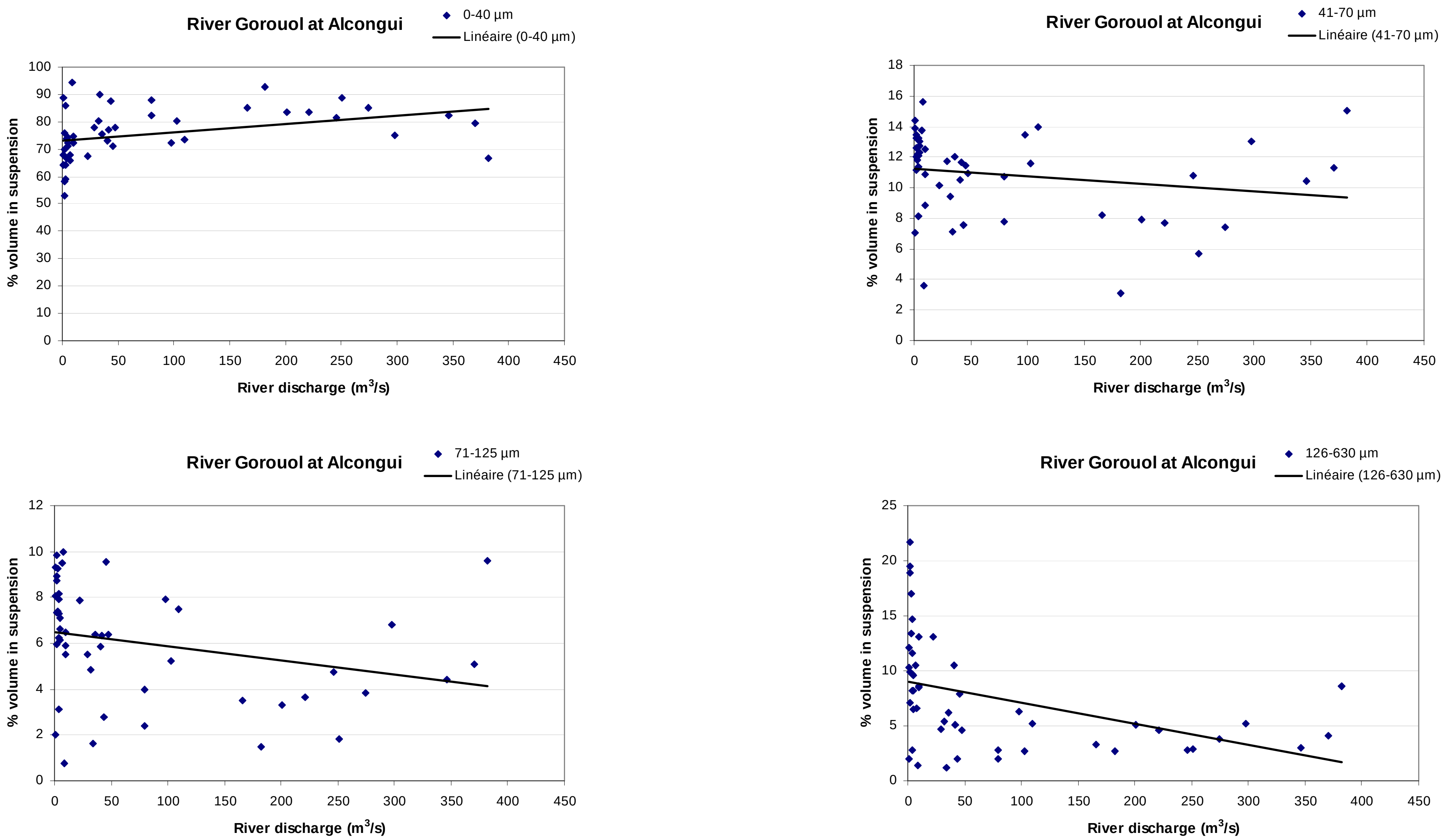
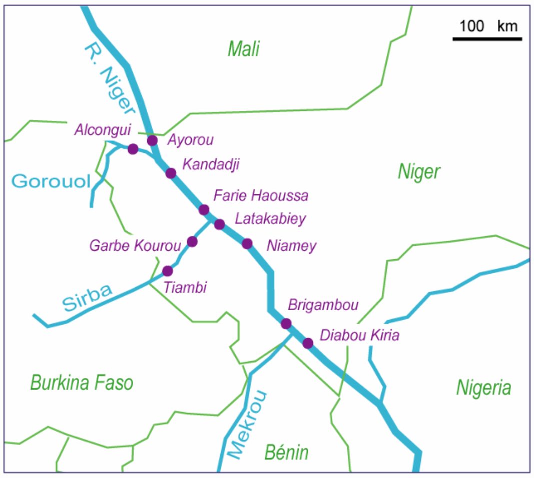


Figure V- 14: River discharge and particle size relationship for the River Gorouol at Alcongui

5.2. Results for the Sirba River



The sediment characteristics of samples collected at Tiambi and at Garbé-Kourou on the River Sirba (see Figure V- 15) in 2006 and 2007 are presented in the following paragraphs. The relationships between SSC, river discharge, and size of sediment in suspension obtained for Tiambi are applicable for Garbé-Kourou.

5.2.1. Riverbed sediments

Analysis of the bed material size of the Sirba River showed an increase in the median particle size between Tiambi and Garbé-Kourou. The median particle size was 385 µm at Tiambi, and 450 µm at Garbé-Kourou. The bed material of the Sirba River is coarser than the bed material of the Gorouol at Alcongui (median particle size was about 220 µm).

5.2.2. Suspended sediment concentrations

At Tiambi, SSC values ranged from 54 mg/l to 2841 mg/l and from 94mg/l to 2282 mg/l. in 2006/07 and 2007/08 respectively. Near the Sirba's confluence with the Niger at Garbé-Kourou, SSC ranged from 130 mg/l to 2917 mg/l and from 196 mg/l to 2696 mg/l in 2006/07 and 2007/08; respectively .The maximum concentration values are almost 1000 mg/l lower than the values measured at the Gorouol at Alcongui.

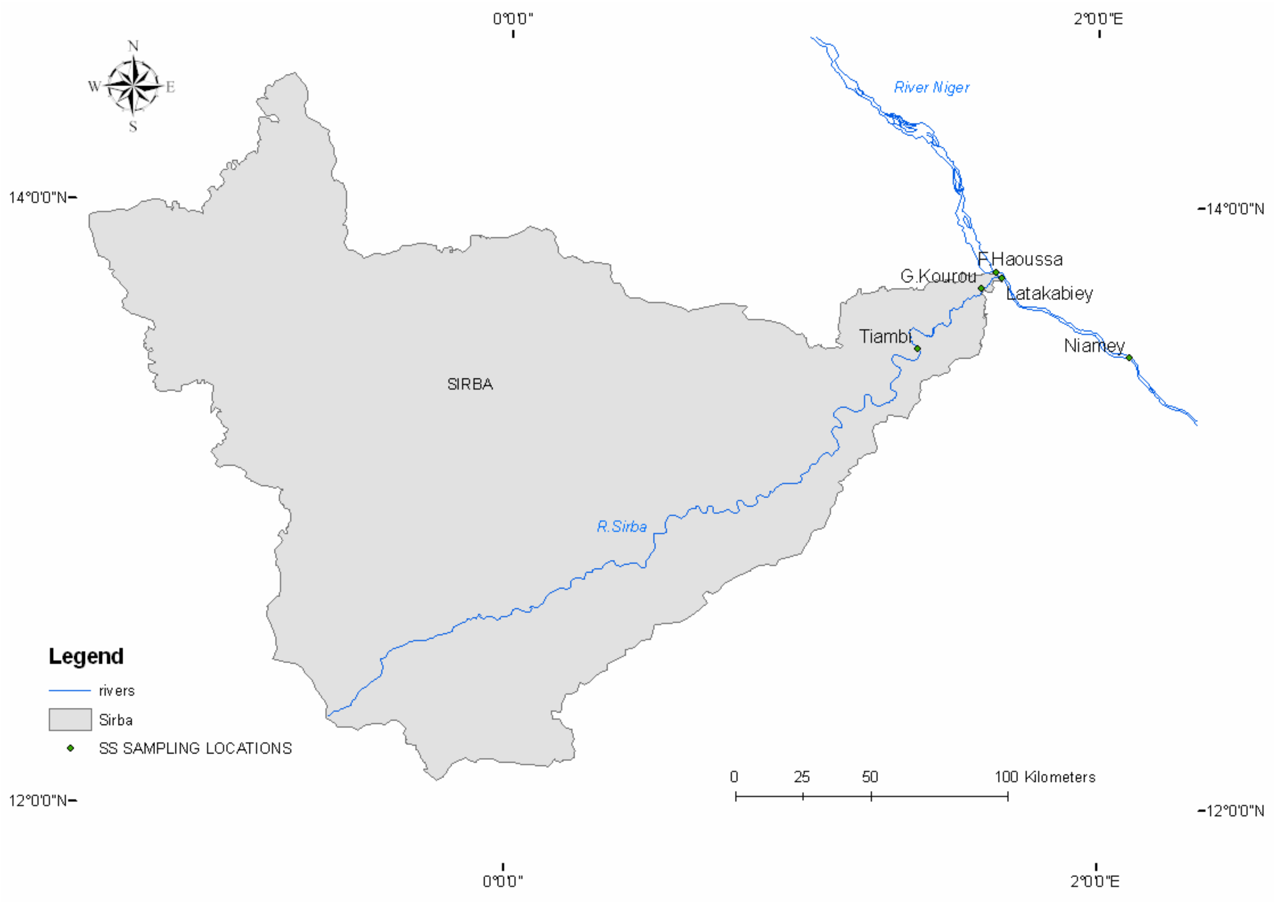


Figure V- 15: The Sirba basin

SSC values at Tiambi and Garbé-Kourou on the Sirba River are plotted alongside river discharge in Figure V- 16 for the 2006/07 and 2007/08 seasons. Unlike the Gorouol at Alcongui, the SSC values for the Sirba River appear to be partly related to river discharge particularly at the start of the runoff season. SSC values do not appear to be as dependent on rainfall events (see Figure V-17) as observed for the Gorouol at Alcongui.

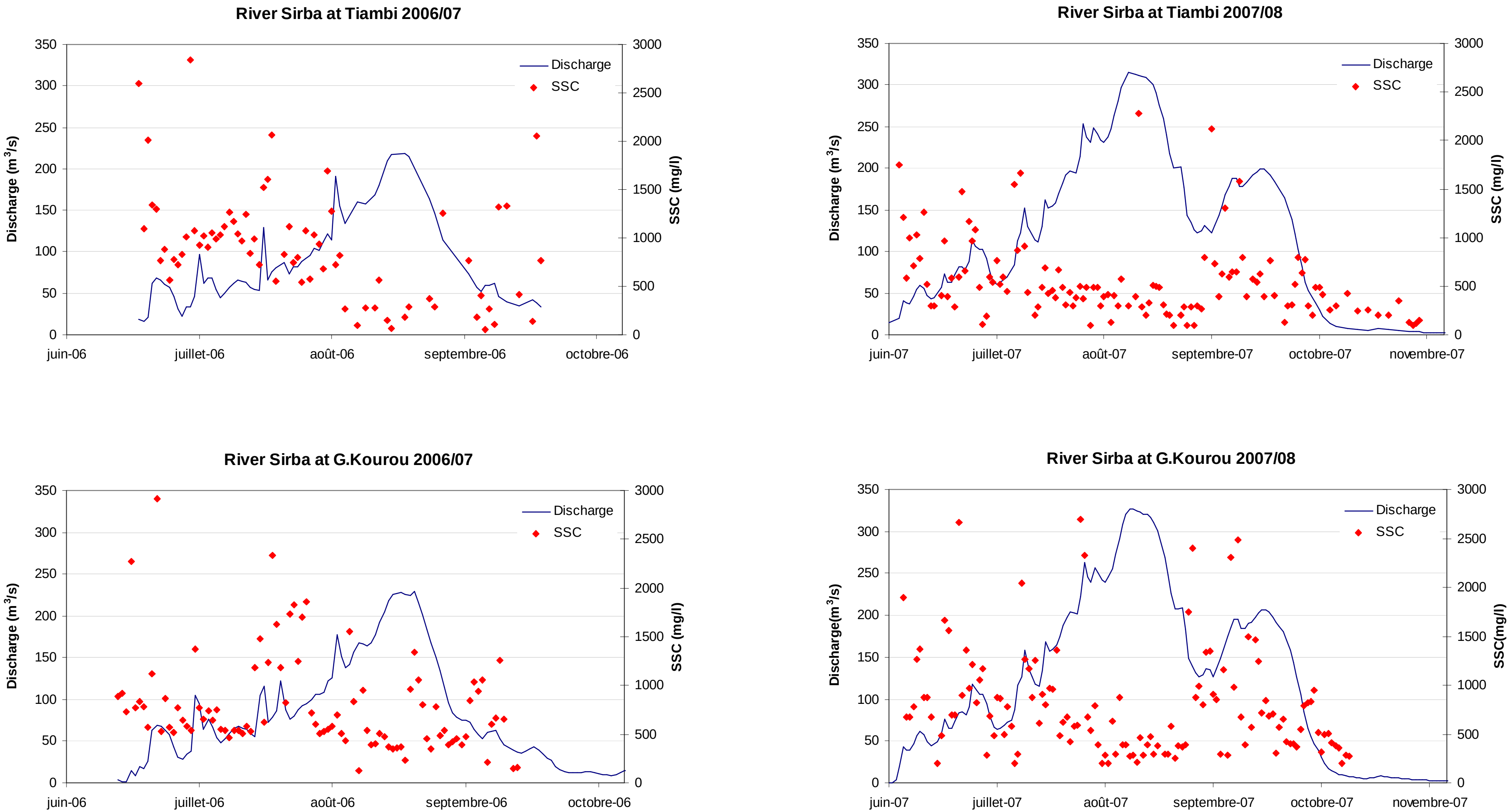


Figure V- 16: River discharge and SSC relationship for the River Sirba at Tiambi and Garbe Kourou (2006 and 2007)

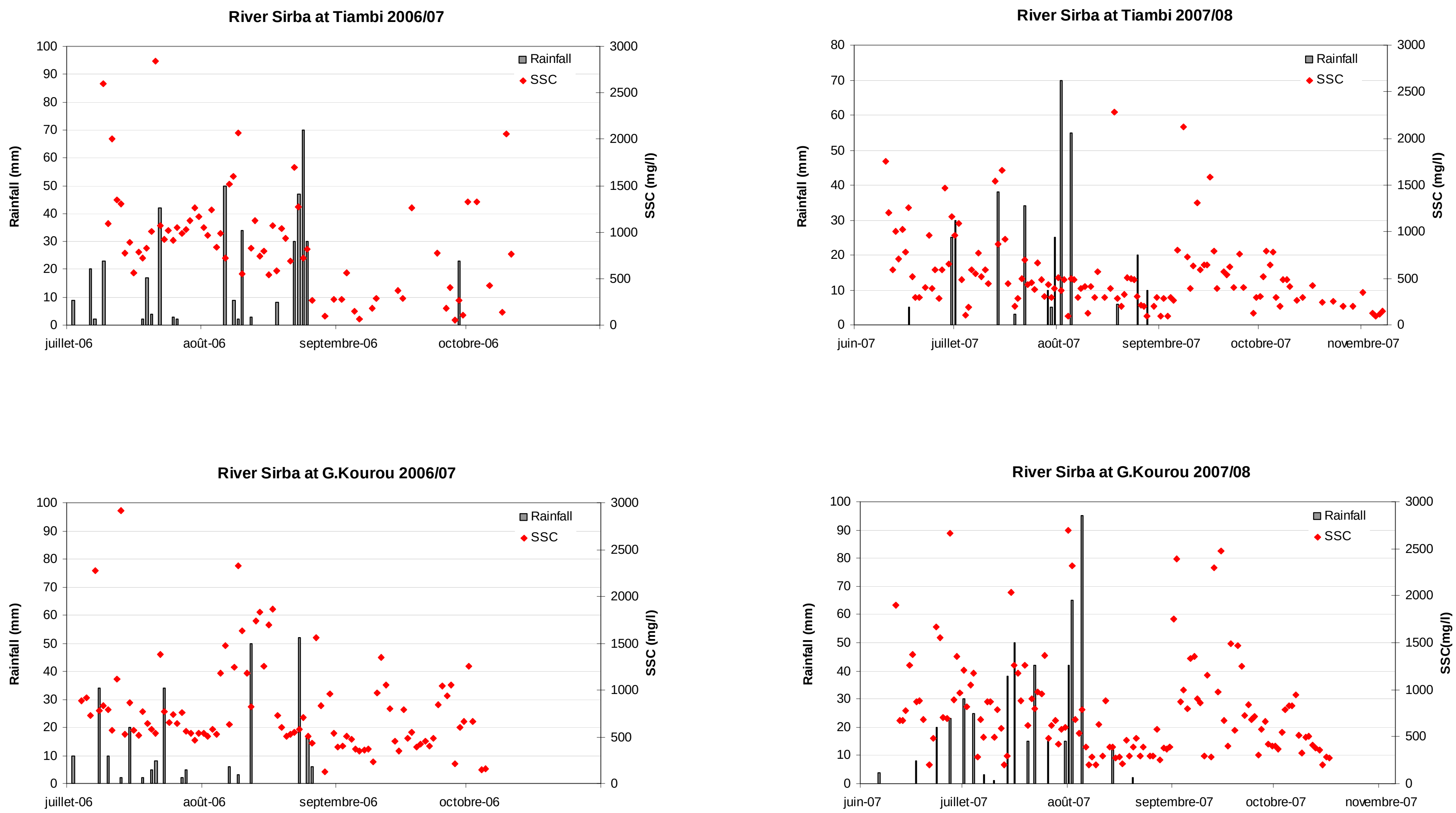


Figure V- 17: At-station rainfall and SSC relationship for the River Sirba at Tiambi and Garbé-Kourou (2006 and 2007)

The concentration values of the sediment size classes present in suspension are presented with corresponding river discharge for the Sirba River at Tiambi and at Garbé-Kourou in Figure V-18.

High concentrations of fine sediment of the clay to medium silt class (0-40 μm) are transported by the Sirba River between the start of the runoff season and the middle of July. During this period, SSC peaks for this class occur at the same time as the discharge peaks that occur on the rising limb of the Sirba's hydrograph. As river discharge continues to increase in mid-July and August, the relative proportions of the 0-40 μm sediment in suspension decreases and the stream flow entrains a greater proportion of larger particles. In particular, at Garbé-Kourou, in August and September, the Sirba transports up to 500 mg/l of sediment particles in the 126-630 μm as well as the 631-1600 μm classes.

The observations for the Sirba River maybe explained by the occurrence of erosion due to the raindrop impact early in the rainy season, transporting the available fine particles at the start of the season until supply is depleted. The Sirba River thereafter begins to transport much larger particles that are likely from the riverbed.

The mean distribution of suspended sediment transported by the Sirba River at Tiambi and at Garbé-Kourou for the 2006/07 and 2007/08 seasons is presented in Figure V- 19. In comparison to the Gorouol River, the Sirba transported a slightly lower percentage of particles in the 0-40 μm class but a higher percentage of the largest sediment class (630-1600 μm).

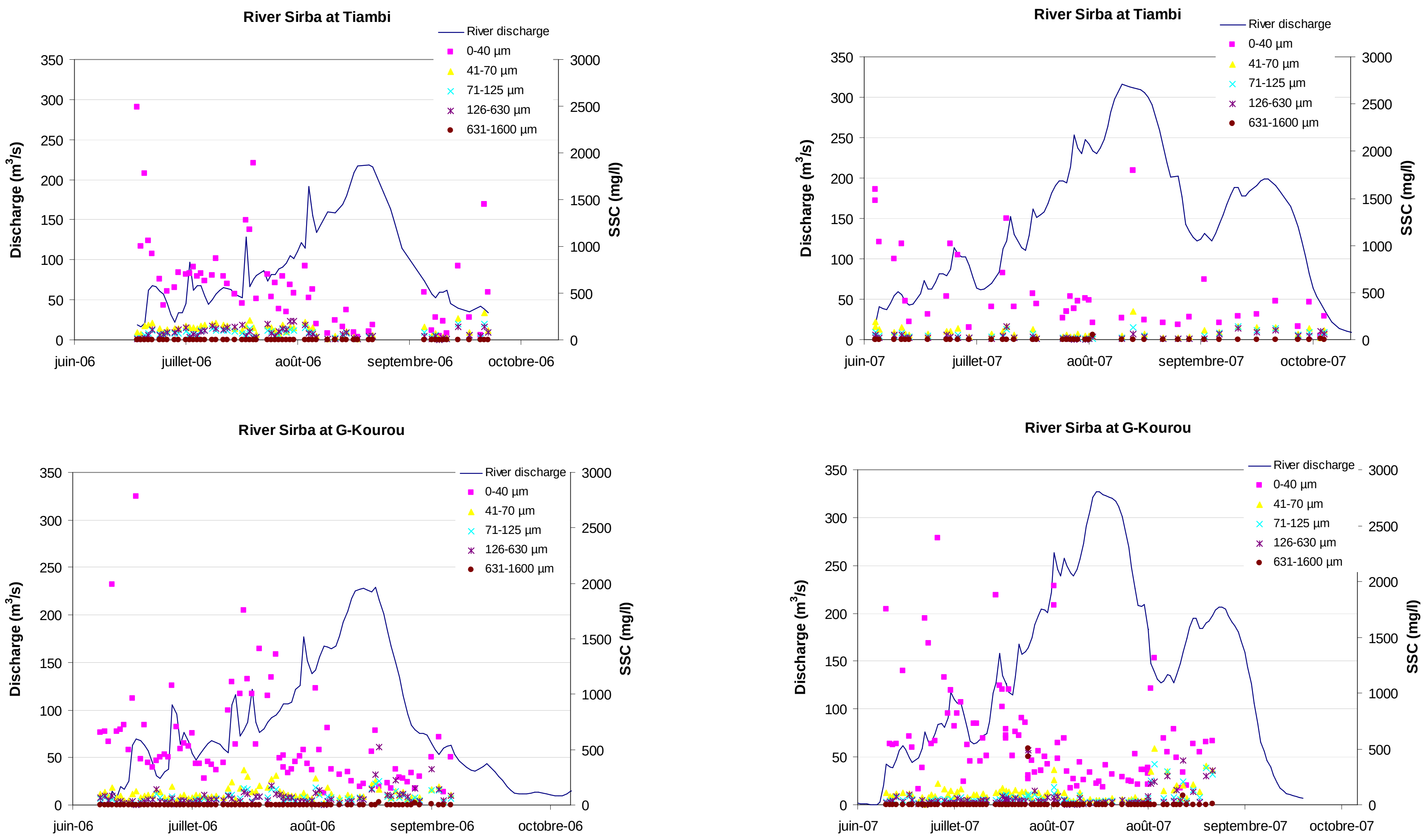


Figure V- 18: River discharge and SSC relationship for the River Sirba (according to size class) at Tiambi and G-Kourou (2006 and 2007)

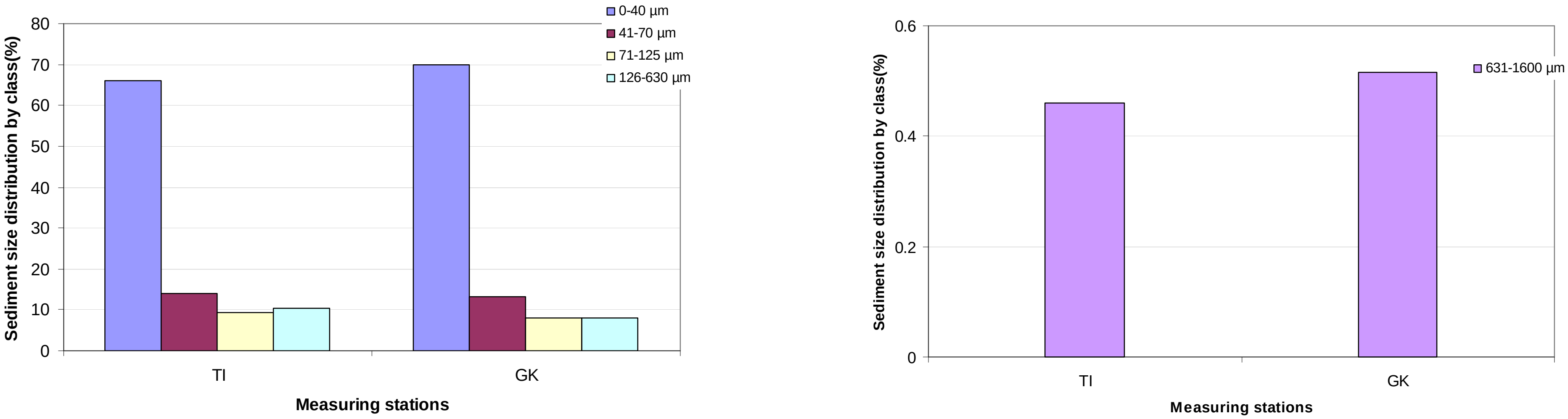


Figure V- 19 : Mean suspended sediment size distribution by percent transported by the River Sirba at Tiambi (n=123 samples) and G-Kourou (n=168 samples)

5.2.3. Changes in sediment particle size distribution

The SSC relationship to sediment grain size transported in the Sirba is similar to the observed 0relationship in the Gorouol. The percentage size composition of the suspended sediment for the Sirba at Tiambi is presented in Figure V- 20. The relationship between the sediment sizes in suspension and SSC is similar to that described for the Gorouol River in Figure V- 13. Figure V- 20, which is also representative of the Sirba at Garbé-Kourou shows that samples with high SSC values are composed of a high percentage of particles in the 0-40 µm class. On the other hand, low concentration sediment samples have a high percentage of coarser particles, and in particular, the 126-630 µm class. The Sirba River transports a higher percentage of particles larger than 40 µm in comparison to the Gorouol River.

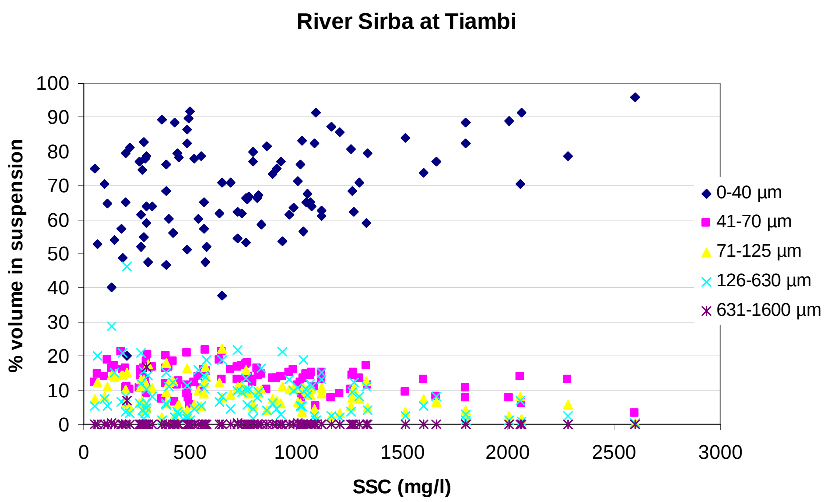


Figure V- 20: SSC and particle size data for the River Sirba at Tiambi

The relationship of four of the suspended sediment size classes with river discharge is described in Figure V- 21 for the Sirba River at Tiambi. Contrary to the relationship observed for the Gorouol at Alcongui, in the Sirba, as river discharge increases, the percentage of 0-40 µm particles in suspension reduces. The percentage of other classes (from 41 µm to 630 µm) transported in suspension increases with increasing river discharge. This appears to indicate that as river discharge increases bed material is eroded and thus the percentage of very fine particles in suspension begins to decrease while large particles begin to increase.

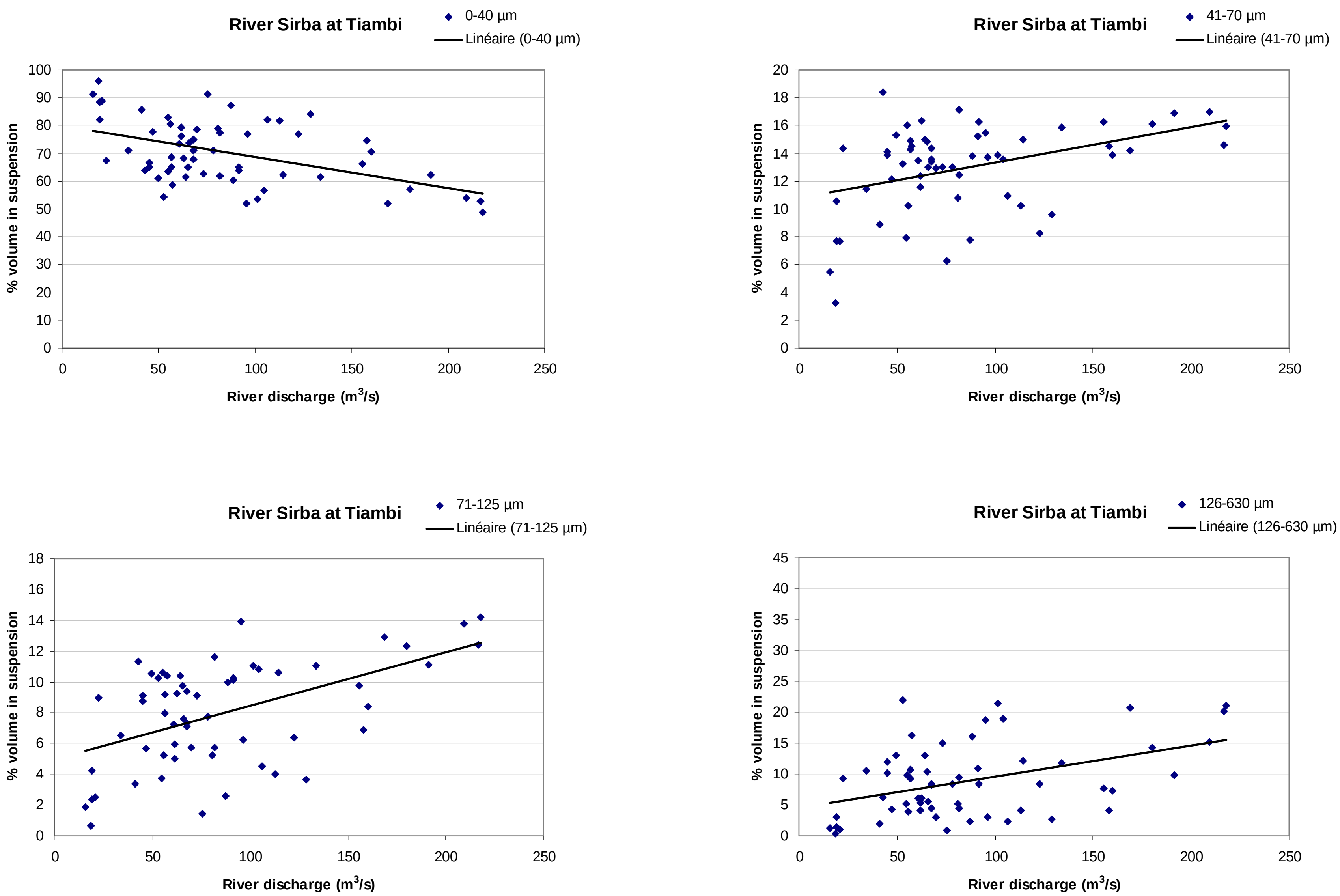


Figure V- 21: River discharge and particle size relationship for the River Sirba at Tiambi

5.3. Discussion of the sediment characteristics in the Sahelian basins

The two Sahelian basins that were studied showed different sediment characteristics. The Gorouol River basin transports finer sediment in comparison to the Sirba basin. The Gorouol carries very fine particles less than 40 µm while the 40-70 µm size class dominates the suspended sediment of the Sirba River. The riverbed material in the Sirba was found to be coarser than the material in the Gorouol. The finest sediment class (0-40 µm) increased with river discharge in the Gorouol River while the reverse was the case in the Sirba River.

As has been noted previously, the variability of SSC in these two river basins is not only due to river discharge but also to precipitation and sediment availability. In addition to the amount of precipitation, the rainfall intensity may provide a better relationship between rainfall and SSC values. The relationship between the median particle size of suspended sediment and river discharge for the Gorouol and Sirba rivers is presented in three subsets each: all data, data for the rising phase of the river's discharge and data for the falling stage of the river's discharge.

The regression coefficients of the fitted curves for the stations on the tributaries are presented in Table V- 5 showing the degree to which river discharge is responsible for the variation in the median size of suspended sediment. The relationship between river discharge and D_{50} is stronger for the rising limb of the tributaries' hydrographs. The median grain size (D_{50}) was related to river discharge by a second-order polynomial equation (Equation V- 2), or by an exponential equation (Equation V- 3).

$$D_{50} = \alpha Q^2 + \beta Q + \gamma$$ **Equation V- 2**

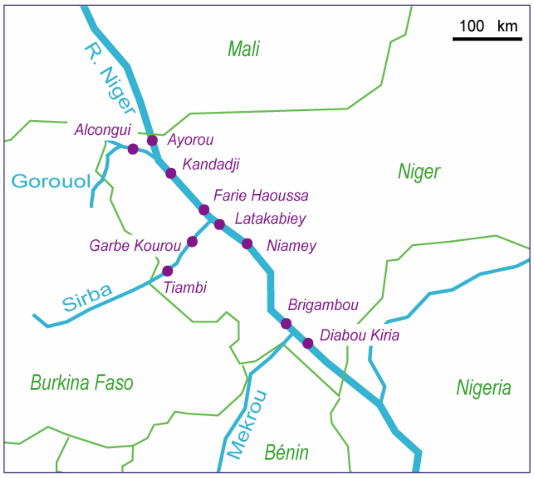
$$D_{50} = \alpha * e^{\beta Q} + \gamma$$ **Equation V- 3**

Table V- 5: River discharge and suspended sediment size relationship for the Gorouol and Sirba rivers

Location	Data	α	β	γ	R²	Equation	N
Alcongui (Gorouol)	All	*22.78*	*-0.0992*	*2.633*10⁻⁴*	*0.1135*	*2° Polynomial*	122
	Rise	*21.55*	*-0.142*	*3.768*10⁻⁴*	*0.4028*	*2° Polynomial*	67
	Fall	*19.01*	*-0.809*	*0.0003*	*0.294*	*2° Polynomial*	25
Tiambi (Sirba)	All	*17.19*	*0.1539*	*-0.0004734*	*0.0756*	*2° Polynomial*	97
	Rise	17.64	0.0038	0	0.33	Exponential	55
	Fall	38.89	-0.001394	0	0.12	Exponential	23
Garbé-Kourou (Sirba)	All	*11.16*	*0.2117*	*-0.0005827*	*0.0935*	*2° Polynomial*	163
	Rise	14.85	0.004253	0	0.24	Exponential	81
	Fall	39.49	-0.001697	0	0.06	Exponential	39

5.4. Results for the middle Niger River

The characteristics of the sediment samples collected at seven locations along the middle Niger River between 2005 and 2008 are presented in the following paragraphs.



5.4.1. Riverbed sediments

An analysis of the bed sediment along the middle Niger River indicated that the median particle size ranged from 120 µm to 450 µm. The median particle size decrease very slightly between Ayorou and Farié-Haoussa, but at Latakabiey, there is a sharp increase in the size of the riverbed material. At Niamey, the median particle size decrease and thereafter continues to increase up to Diabou-Kiria (see Figure V- 22). At the stations along the middle Niger River, sand sized particles (>63 microns) make up between 90 to 100% of the riverbed material except at Farié-Haoussa where 10% of the riverbed material are less than 55 µm.

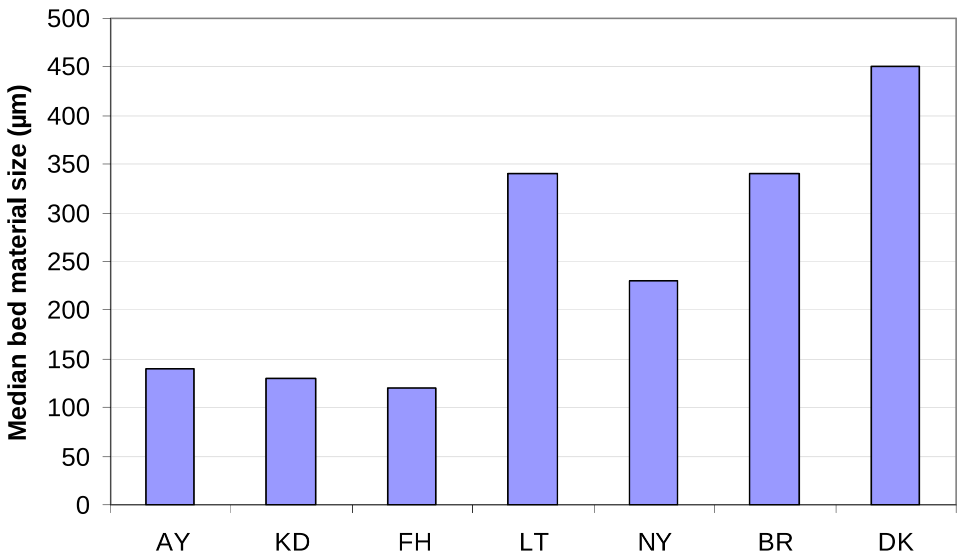
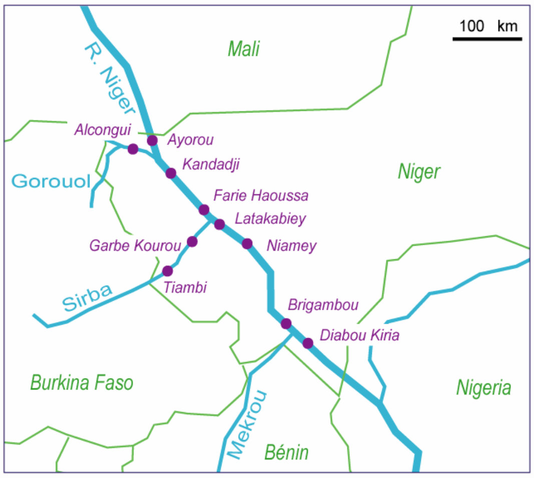


Figure V- 22: Mean bed material size along the middle Niger River

The size of riverbed material typically decreases with increasing distance downstream and is attributed to a combination of abrasion, weathering and selective entrainment of finer particles. It has been recognized that tributaries can disrupt these fining patterns [*J E Pizzuto*, 1995].

The slight decrease in the median particle size of riverbed material between Kandadji and Farié-Haoussa may indicate that the Dargol River (the tributary between the two stations) does not create a discontinuity in riverbed material size as observed for the Sirba-Niger confluence. On the other hand, the other tributaries between Niamey and Brigambou (the Goroubi, the Diamangou and the Tapoa) may have a significant effect on the riverbed material size of the middle Niger River. According to Hooke [2003], insufficient transporting capacity to transport coarse sediment may produce an " unconnected system" or discontinuity in the size of riverbed material as occurs at Latakabiey along the middle Niger River. The sizes of bed material of the Sirba River at Tiambi and garbe-Kourou may affect the increase in bed material size observed between Farié-Haoussa and Latakabiey.

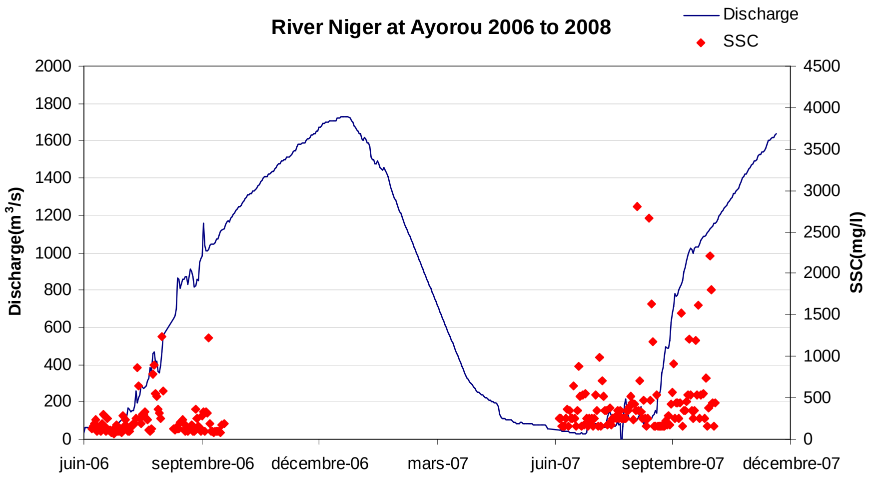
5.4.2. Suspended sediment concentrations

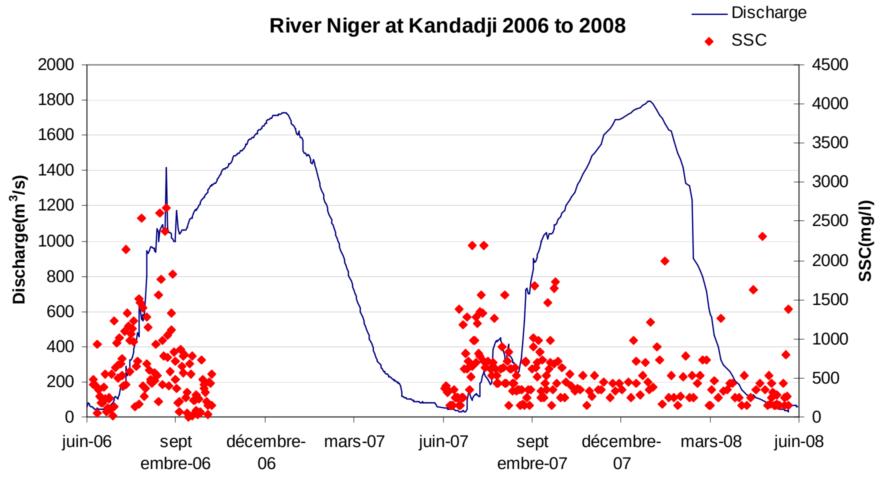


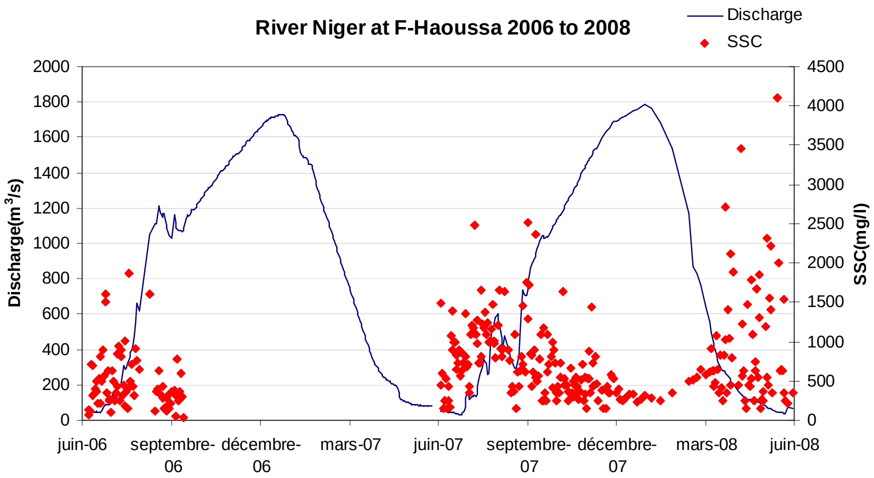
Suspended sediment sampling started at Niamey in December 2005, while sampling at the other stations began in June 2006. In the first sampling season (2006/07), sampling at all stations except at Niamey was from June to October only. This was in order to evaluate the effect of the local rainy season and tributary sediment flux on the River Niger. For the second season, an attempt was made to continue sampling throughout the hydrological year, by sampling daily between June and October and at 3-day intervals between November and May, because it was assumed that sediment transport in the latter period shows less variation with time. Sampling at Ayorou stopped in October 2007 due to operational problems while at Niamey sampling was interrupted between January 2008 and March 2008. Figure V- 23 displays the relationship between mean cross-sectional SSC and river discharge along the middle Niger River, for the period of measurement.

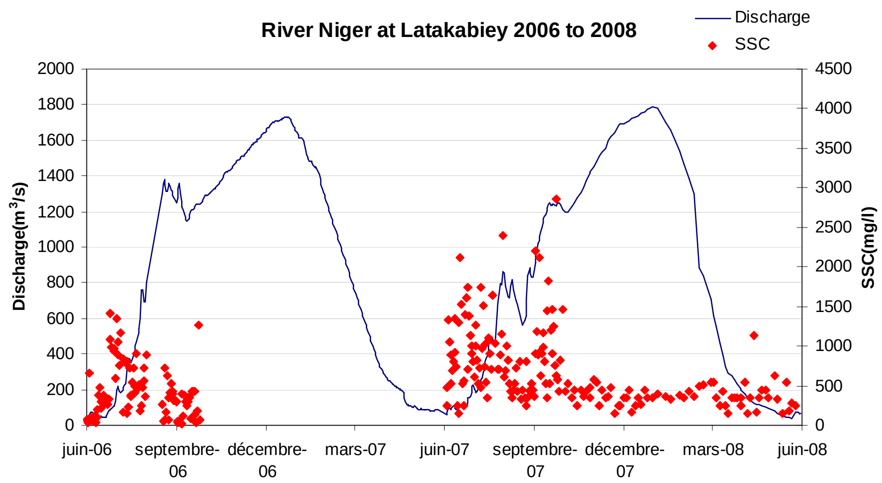
SSC values in the middle Niger River for the study period ranged from about 7 mg/l to over 4000 mg/l. The clearest distinction between SSC values in the rainy season and dry season is observed for the southern part of the middle Niger River (Brigambou and Diabou-Kiria), where concentrations reach 1500 mg/l between June and October and are rarely above about 500 mg/l in the dry season.

Data from the present study shows that in general the highest sediment concentrations in the middle Niger River occur between June and August (see Figure V- 23). Figure V- 23 shows that in addition to high sediment concentration values between June and August, high SSC values were observed at the Niger at Kandadji and Farié-Haoussa between January and April. At the Niamey station, in addition to the peak SSC values that occur between June and August SSC values remain relatively stable throughout the year dropping well below 500 mg/l only between April and May.


River Niger at Ayorou 2006 to 2008
Discharge
SSC
Discharge(m³/s)
SSC(mg/l)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
500
1000
1500
2000
2500
3000
3500
4000
4500
juin-06
septembre-06
décembre-06
mars-07
juin-07
septembre-07
décembre-07


River Niger at Kandadji 2006 to 2008
Discharge
SSC
Discharge(m³/s)
SSC(mg/l)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
500
1000
1500
2000
2500
3000
3500
4000
4500
juin-06
sept embre-06
décembre-06
mars-07
juin-07
sept embre-07
décembre-07
mars-08
juin-08


River Niger at F-Haoussa 2006 to 2008
Discharge
SSC
Discharge(m³/s)
SSC(mg/l)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
500
1000
1500
2000
2500
3000
3500
4000
4500
juin-06
septembre-06
décembre-06
mars-07
juin-07
septembre-07
décembre-07
mars-08
juin-08


River Niger at Latakabiey 2006 to 2008
Discharge
SSC
Discharge(m³/s)
SSC(mg/l)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
500
1000
1500
2000
2500
3000
3500
4000
4500
juin-06
septembre-06
décembre-06
mars-07
juin-07
septembre-07
décembre-07
mars-08
juin-08

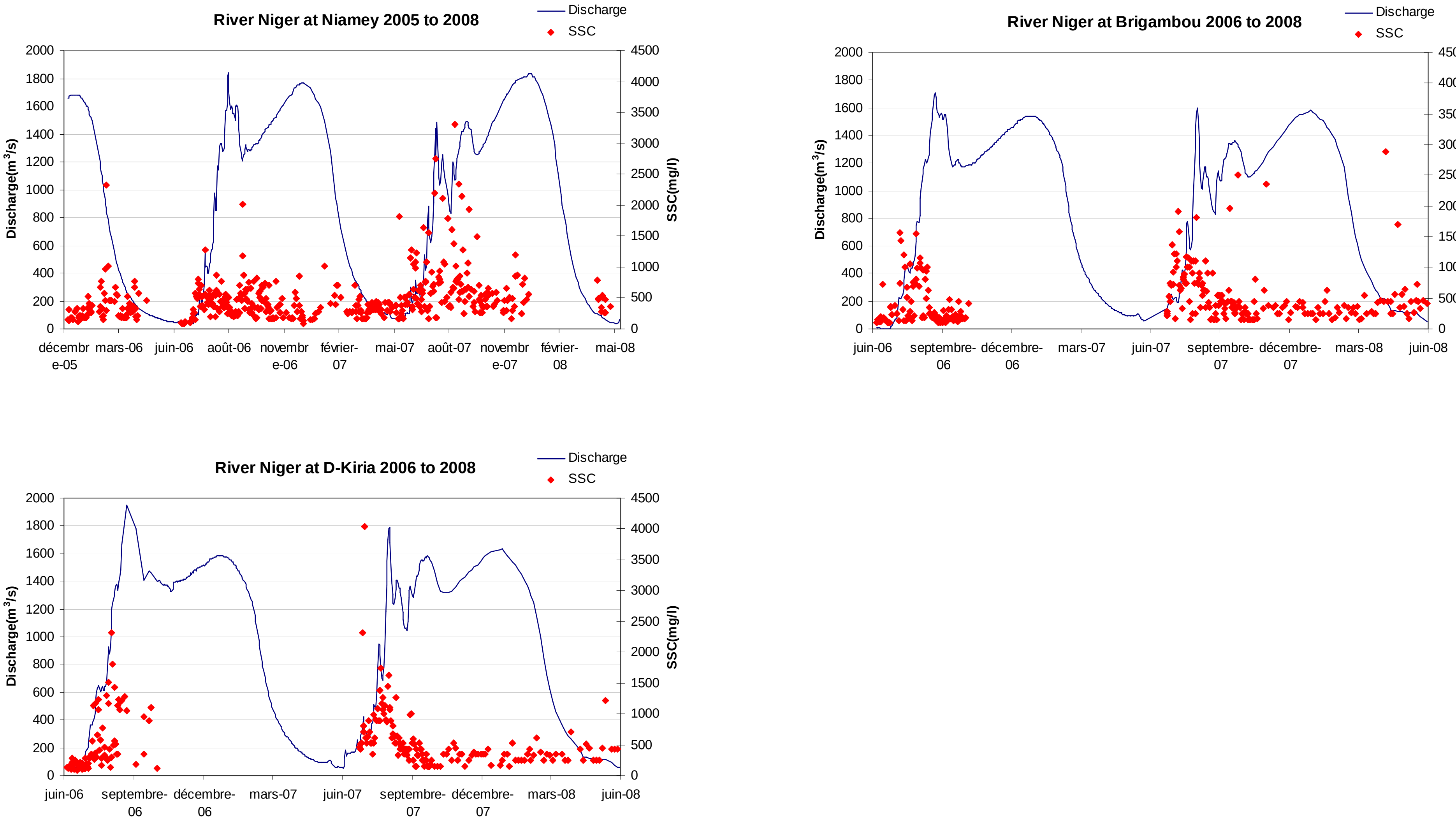
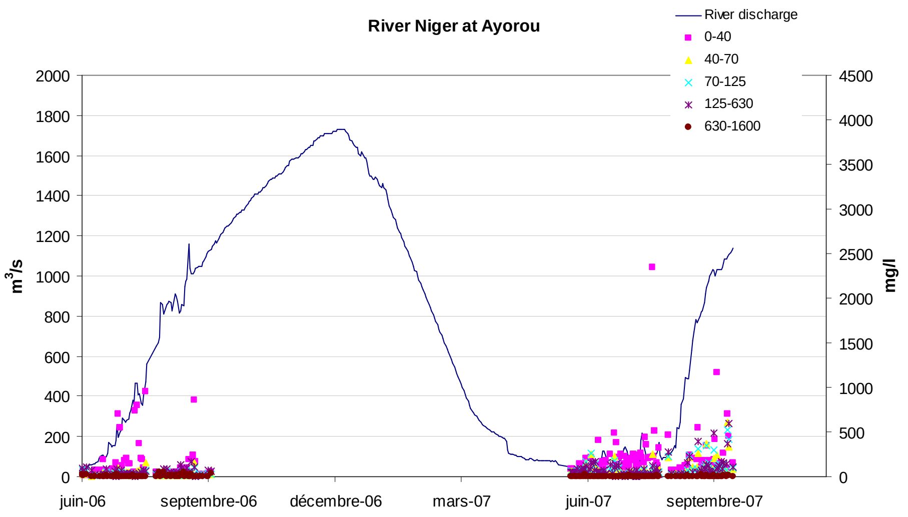


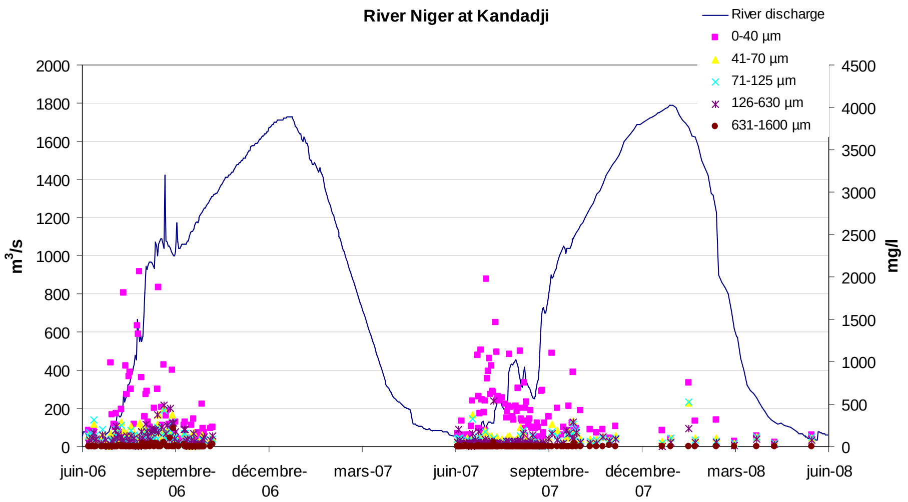
Figure V- 23: River discharge and SSC relationship for the middle Niger River.

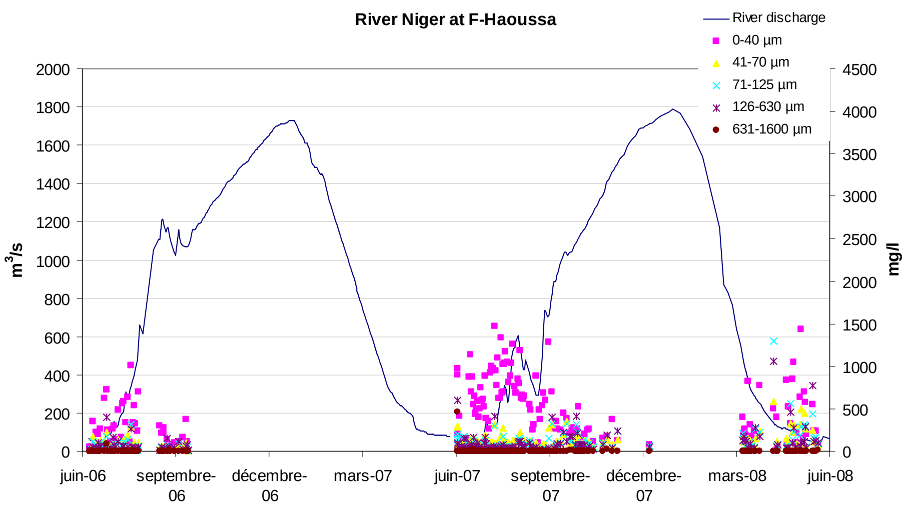
The particle size distribution of some of the suspended sediment samples was determined and is presented in relationship to river discharge and SSC in Figure V- 24. For each station, the particle size distribution of between 130 and 200 samples was analysed in order to gain a better understanding of the relative amounts of each sediment size class transported during the different sediment transport phases observed in Figure V- 23.

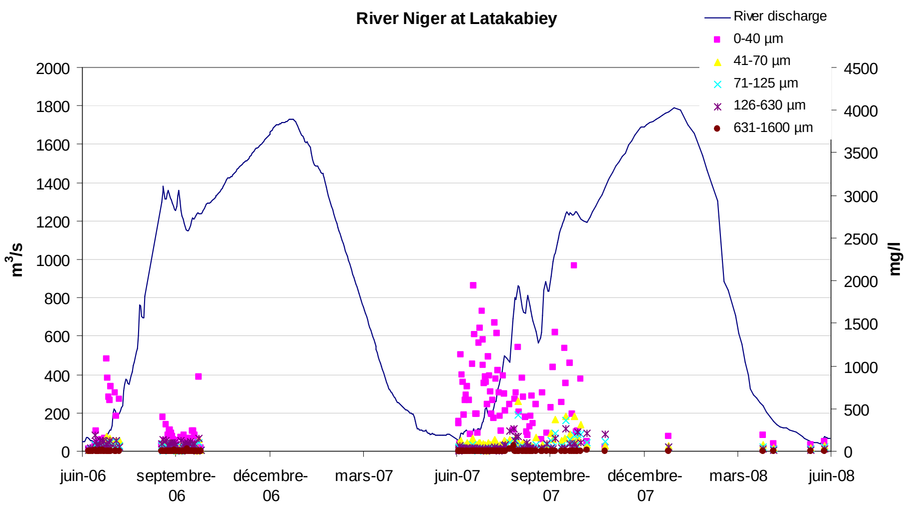
The first SSC peak that is common to all the stations is due to the local rainy season and tributary sediment discharge to the Niger River. Figure V- 24 supports this assertion because it shows that the observed high SSC values between June and August are mainly composed of sediment in the 0-40 μm size class.

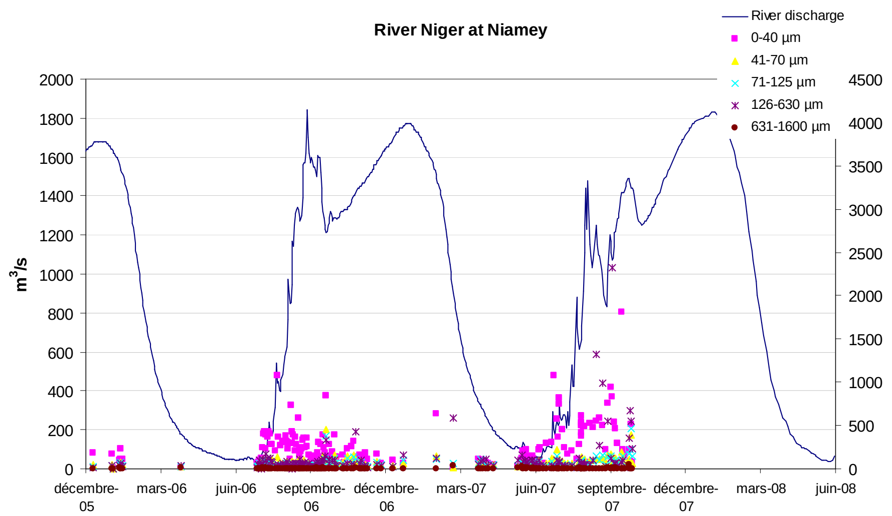
The second period of high SSC values observed at Kandadji and Farié-Haoussa between January and April (see Figure V- 23) are composed mainly of larger sized sediment particles. It is apparent that this increase in sediment concentration occurring in the dry season is not due to tributary contribution or rainfall effects because they consist mainly of coarse particles and is possibly due to sediment transfer from upstream of the study area (the Niger's interior delta). Figure V- 24 shows that these high SSC values are composed mainly of relatively large sediment particles in the fine to medium sand range (71 to 630 μm).

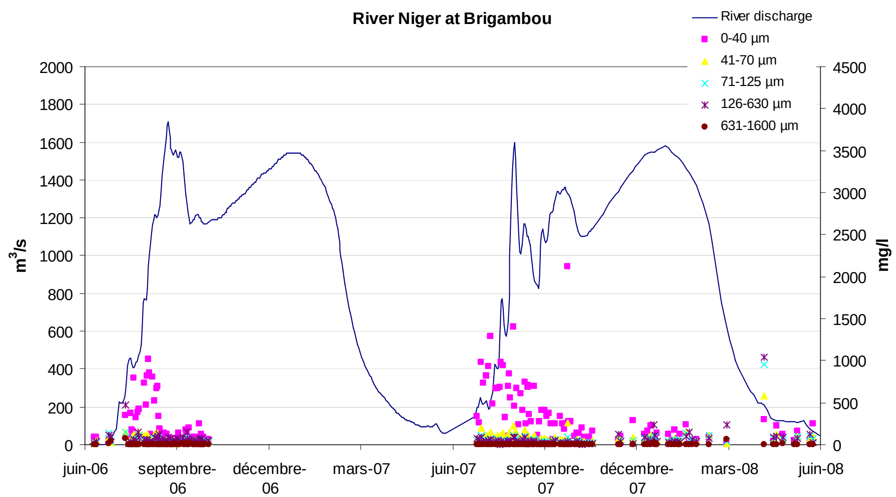

River Niger at Ayorou
River discharge
0-40
40-70
70-125
125-630
630-1600
m³/s
mg/l
juin-06
septembre-06
décembre-06
mars-07
juin-07
septembre-07


River Niger at Kandadji
River discharge
0-40 µm
41-70 µm
71-125 µm
126-630 µm
631-1600 µm
m³/s
mg/l
juin-06
septembre-06
décembre-06
mars-07
juin-07
septembre-07
décembre-07
mars-08
juin-08


River Niger at F-Haoussa
River discharge
0-40 µm
41-70 µm
71-125 µm
126-630 µm
631-1600 µm
m³/s
mg/l
juin-06
septembre-06
décembre-06
mars-07
juin-07
septembre-07
décembre-07
mars-08
juin-08


River Niger at Latakabiey
River discharge
0-40 µm
41-70 µm
71-125 µm
126-630 µm
631-1600 µm
m³/s
mg/l
juin-06
septembre-06
décembre-06
mars-07
juin-07
septembre-07
décembre-07
mars-08
juin-08





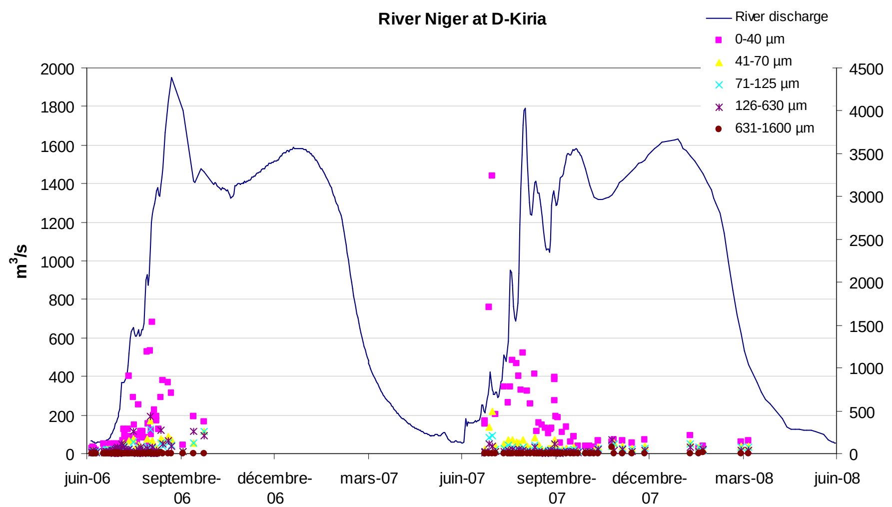
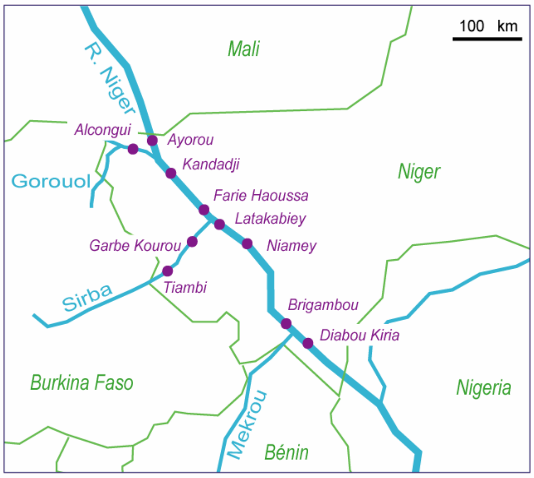


Figure V- 24: River discharge and SSC relationship (according to size class) for the middle Niger River

In general, at most of the stations along the middle Niger River, it was observed that the first hydrograph peak that occurs during the rainy season between June and September transports a high percentage of the finest sediment class. The exception is the Niamey station, where high concentrations of sediment particles in the 126 µm to 630-µm class are transported between August and September (see Figure V- 24).



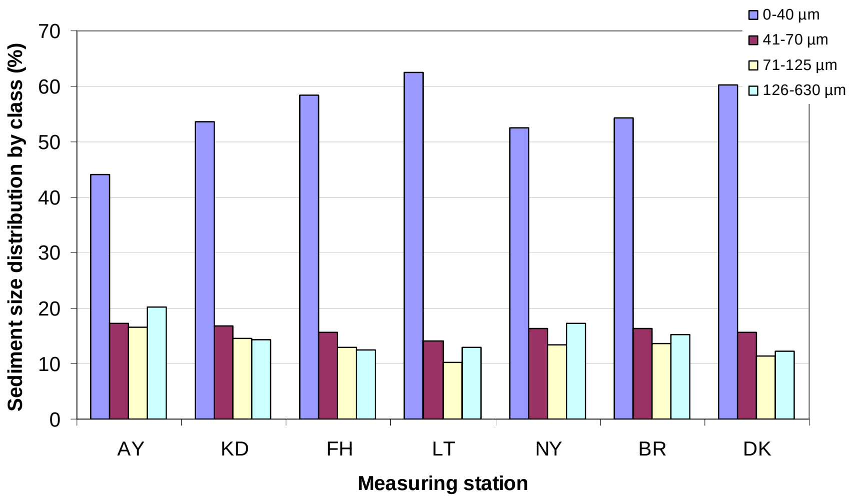
Considering that this behaviour was not observed at other stations along the Niger, and that there are no conventional tributaries between Latakabiey and Niamey, this incidents may be due to such point sources as the "koris" that have been observed around Niamey. In addition, significant transport of the 126-630 µm sediment class was not observed downstream of Niamey at Brigambou indicating that deposition of this size of sediment may be expected between Niamey and Brigambou. Further investigation on the characteristics of the sediment transported by these "koris" is required to confirm this supposition.

The mean distribution of suspended sediment transported by the middle Niger River during the study period is presented as histograms in Figure V- 25 (Ayorou *AY*, Kandadji *KD*, Farié-Haoussa *FH*, Latakabiey *LT*, Niamey *NY*, Brigambou *BR*, Diabou-Kiria *DK*).

The plot showing the size composition of the sediment transported in suspension indicates that the 0-40 µm size class increases along the Niger River from Ayorou up to Latakabiey. Between Latakabiey and Niamey, the percentage of the 0-40 µm transported reduces abruptly, and then increases again from Niamey to Diabou-Kiria. This could indicate that there is a zone of sediment transfer discontinuity between Latakabiey and Niamey or that there exists a sediment source zone supplying coarse sediment to the Niger River between these two stations.

The opposite behaviour is observed for all the other size classes:, the percentage in suspension of the 41-70 µm, the 71-125 µm and the 630-1600 µm size classes decrease steadily downstream from Ayorou to Latakabiey, increase at Niamey and then continue decreasing downstream to Diabou-Kiria. The abrupt decrease in the 630-1600 µm size class between Ayorou and Kandadji is due to a decrease in bed shear velocity between the two stations as well as the effect of the Gorouol River's fine sediment input that is preferentially transported.

The exception is the 126-630 µm (fine to medium sand) class, which decreases in the downstream direction from Ayorou to Farié-Haoussa. At Latakabiey, there is a slight increase in the percentage of this size class, and a further increase at Niamey.



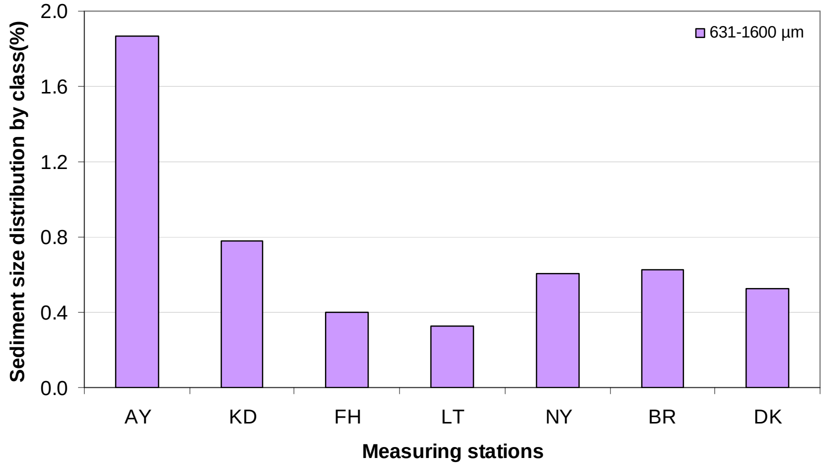


Figure V- 25 : Mean suspended sediment size distribution by percent transported by the middle Niger River

5.4.3. Changes in mean SSC along the middle Niger River by size class

The mean value SSC transported by size class between 2006 and 2008 at stations along the middle Niger River are presented in Figure V- 26 and Figure V- 27 . SSC values for the 0-40 µm class are represented along the principal y-axis, while the SSC values for the coarser size classes(41-125 µm) are represented on the secondary y-axis in Figure V- 26. The entry points of the middle Niger's tributaries are shown between the stations in Figure V- 26 and Figure V- 27. Mean SSC values of the 631-1600 µm size class are presented in Figure V- 27

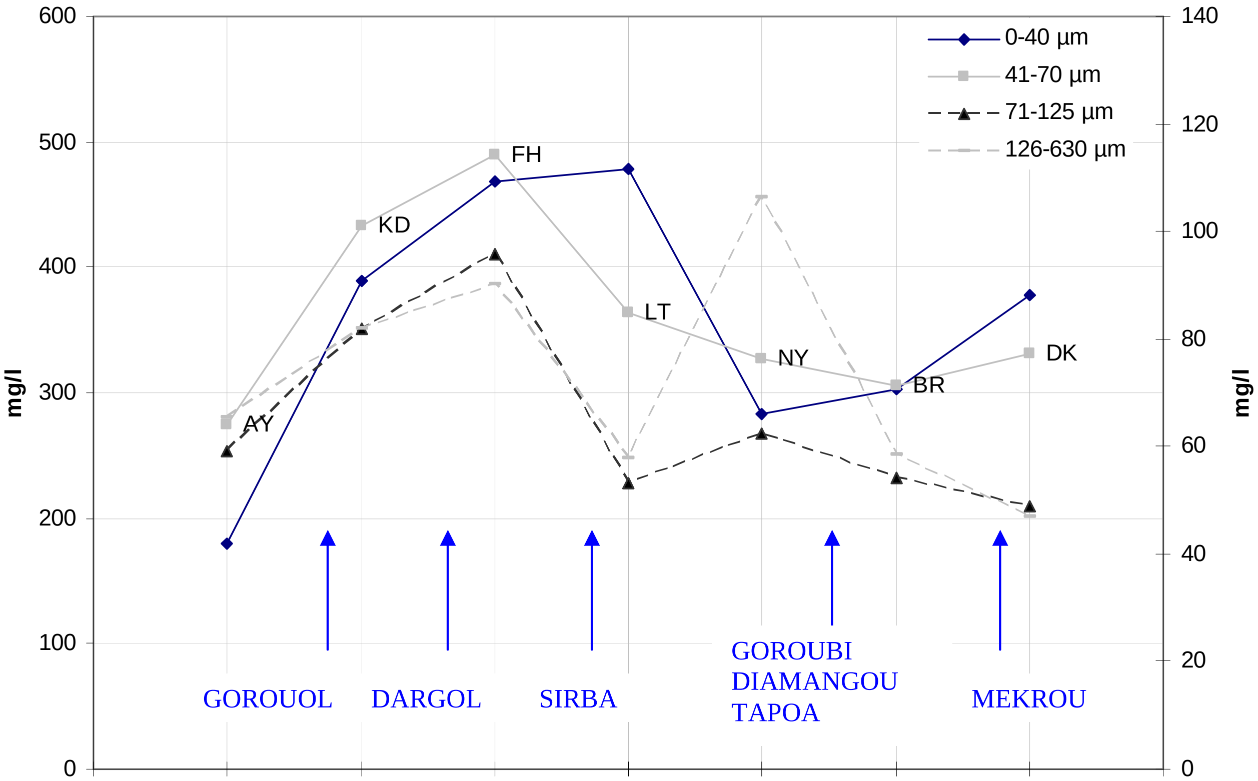


Figure V- 26 : Mean SSC values transported along the middle Niger River (0-630 µm)

The plot of mean sediment concentration over the study period measured at seven stations along the Niger River indicates the following behaviour for the five sediment classes:

- Clay to medium silt (0-40 µm): The mean concentration of this class increases exponentially between Ayorou (180 mg/l) and Latakabiey (470 mg/l). After Latakabiey, the mean sediment concentration of the 0-40 µm sediment diminishes at Niamey before increasing slightly at Brigambou. A further increase in the mean concentration of this sediment class at Diabou-Kiria is observed and is possibly due to fine sediment supply from the Mékrou River

- Coarse silt (41-70 µm): The concentration of this grain size class increases along the middle Niger River in a downstream direction but unlike the 0-40 µm class, it reaches a peak at Farié-Haoussa. Between Farié-Haoussa and Brigambou, the concentration of this sediment class continues to decrease. At Diabou-Kiria, like for the 0-40 µm class, an increase in the sediment concentration of the 41-70 µm class was observed.
- Very fine sand (71-125 µm): The mean concentration of very fine sand increases between Ayorou and Farié-Haoussa. At Latakabiey, the concentration of this sediment class decreases, increasing again slightly at Niamey. After Niamey, the concentration of very fine sand in suspension decreases progressively up until Diabou-Kiria.
- Fine to medium sand (126-630 µm): The trend observed for the very fine sand class is repeated for this class of sediment in suspension. The only difference is that the increase in concentration of the fine to medium sand class between Latakabiey and Niamey is more abrupt.

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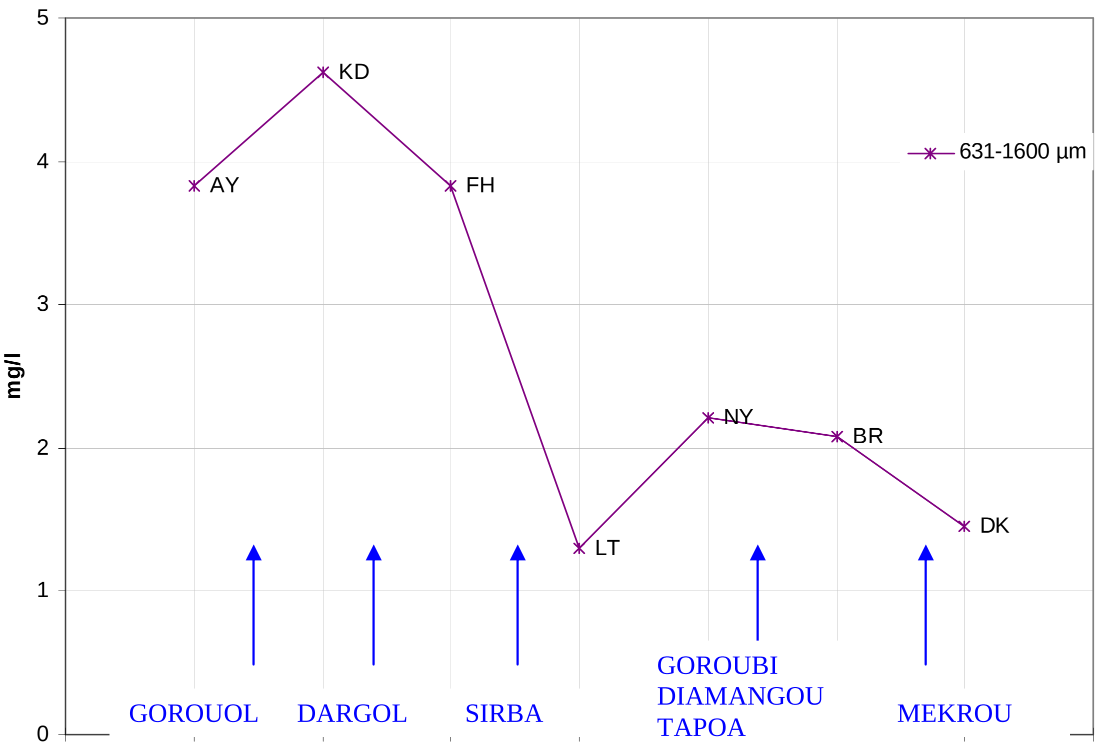


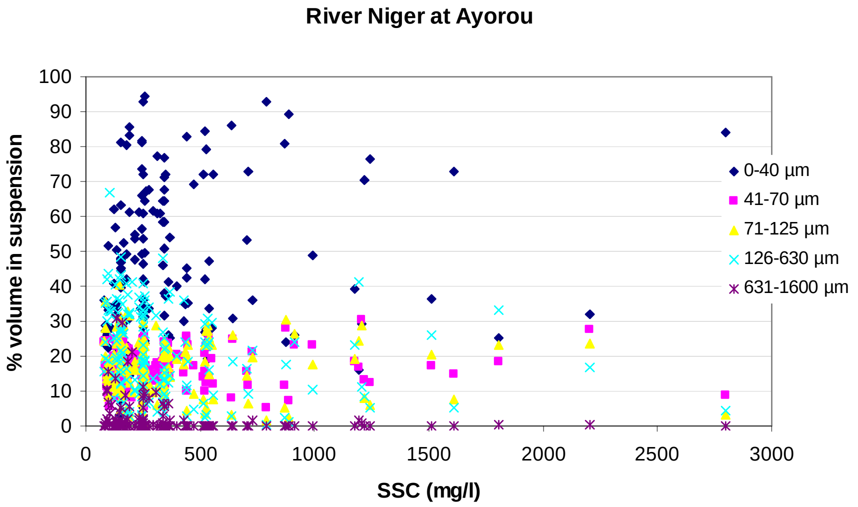
Figure V- 27 : Mean SSC values transported along the middle Niger River (631-1600 µm)

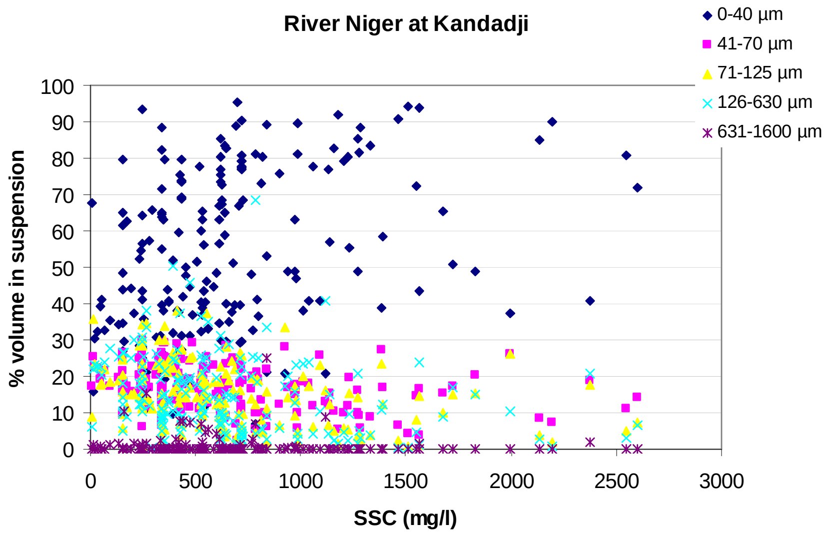
- Coarse to very coarse sand (631-1600 µm): The concentration of coarse sand transported in suspension along the middle Niger is relatively high between Ayorou and Farié-Haoussa and low thereafter. Between Ayorou and Farié-Haoussa, the concentration of this size class in suspension increases at Kandadji and then decreases at Farié-Haoussa. A sharp fall in the concentration of coarse sand is observed between Farié-Haoussa and Latakabiey. A slight increase in the concentration of coarse sand occurs between Latakabiey and Niamey, after which its concentration decreases until Diabou-Kiria.

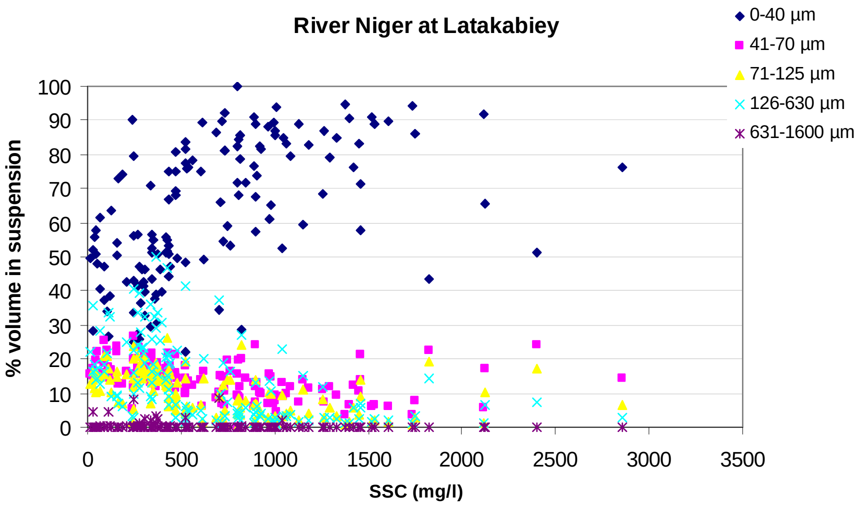
A summary of the observations for stretches between the measuring stations along the middle Niger River can be made as follows:

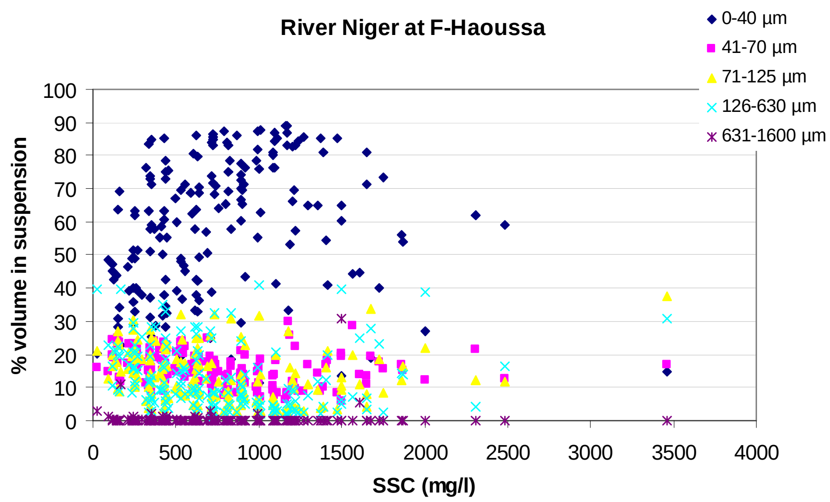
- Ayorou to Kandadji: The concentration of all sediment classes increase between Ayorou and Kandadji, indicating the availability of all classes of sediment. The median size of the bed material measured at Ayorou was 130 µm and about 98% of the particles were larger than about 100 µm. It can therefore be assumed that the very fine sediment transported in this stretch is mainly due to land erosion between Ayorou and Kandadji.
- Kandadji to Farié-Haoussa: The trend of increasing sediment concentration for all classes continues between Kandadji and Farié-Haoussa.
- Farié-Haoussa to Latakabiey: The concentration of the finest sediment class (0-40 µm) increases while the concentration of all sediment larger than 40 µm decreases. The supply and transfer of washload can be observed between Farié-Haoussa and Latakabiey. The decrease in concentration of all sediment sizes larger than 40 µm indicates sediment deposition. This may also explain the relatively large size of the riverbed material at Latakabiey. The median grain size was 340 µm and the 10% of the bed material was less than 140 µm.
- Latakabiey to Niamey: Between Latakabiey and Niamey it was observed that the concentration of sediment sizes less than 70 µm reduced while the concentration of sediment sizes larger than 70 µm increased. This indicates a difference in the sources of sediment between the two stations.
- Niamey to Brigambou: An increase in fine sediment concentration was observed between Niamey and Brigambou. A reduction of the mean concentration of all sizes larger than 40 µm occurs between Niamey and Brigambou indicating the deposition of sediment greater than about 40 µm.
- Brigambou to Diabou-Kiria: The sediment concentration of the sizes less than 70 µm increases while the concentration of sediment larger than 70 µm decreases. This is an indication of the size of sediment supplied by the Mékrou River (<70 µm).

The SSC and particle size data for the stations along the middle Niger River is presented in Figure V-28 and they show a similar relationship to varying degrees to the observations for the Gorouol river see Figure V- 13.


River Niger at Ayorou
% volume in suspension
SSC (mg/l)
0-40 µm
41-70 µm
71-125 µm
126-630 µm
631-1600 µm


River Niger at Kandadji
% volume in suspension
SSC (mg/l)
0-40 µm
41-70 µm
71-125 µm
126-630 µm
631-1600 µm


River Niger at Latakabiey
% volume in suspension
SSC (mg/l)
0-40 µm
41-70 µm
71-125 µm
126-630 µm
631-1600 µm


River Niger at F-Haoussa
% volume in suspension
SSC (mg/l)
0-40 µm
41-70 µm
71-125 µm
126-630 µm
631-1600 µm

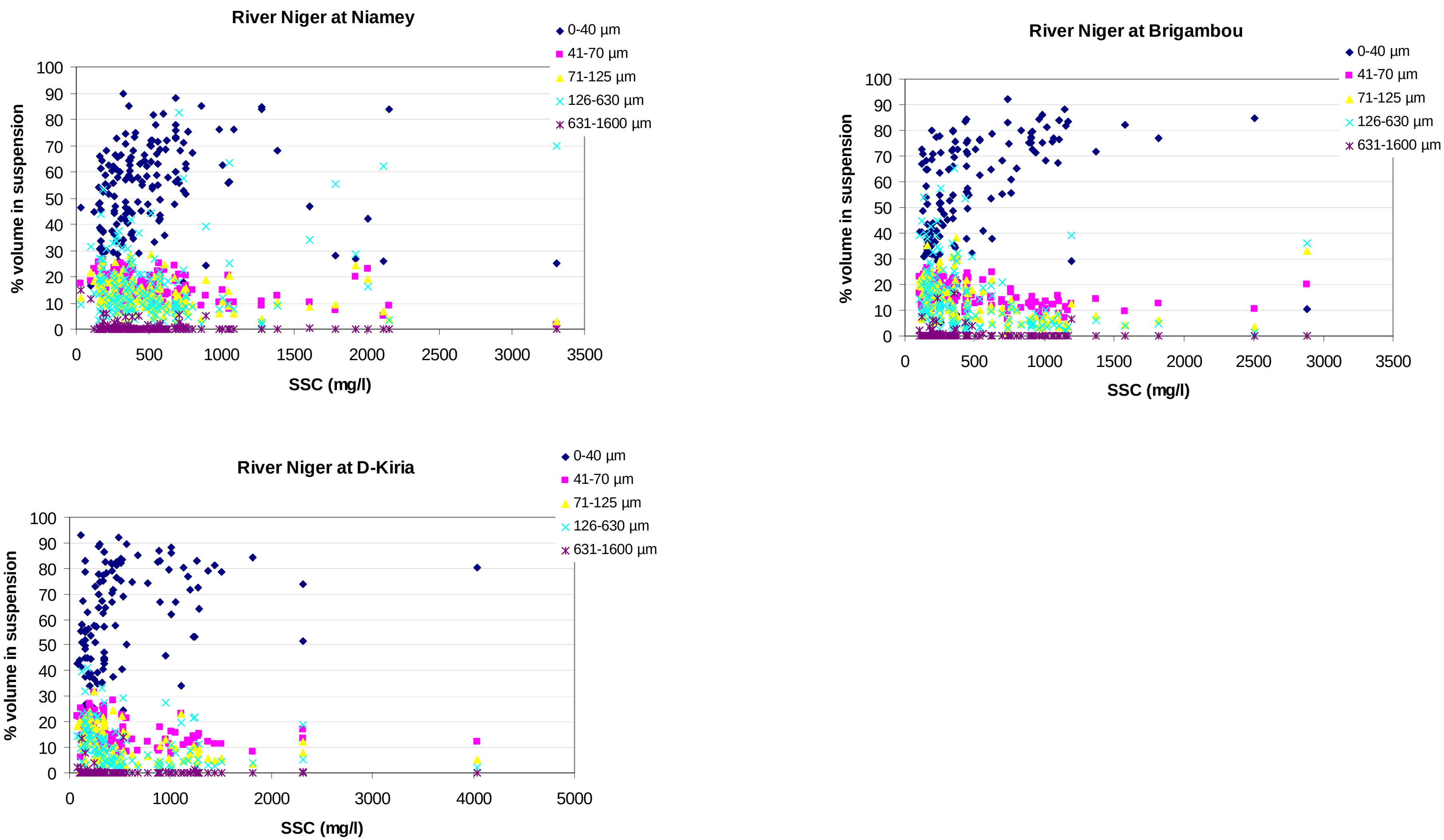


Figure V- 28: SSC and particle size data for the middle Niger River

5.4.4. Seasonal effects on the river discharge-SSC relationship

Two peaks characterize the middle Niger River's hydrograph; the first peak is due to tributary contribution during the local rainy season (in August or September) and the second peak that occurs in December or January is due to the peak of the Upper Niger River delayed due to the buffering action of the inland delta. It was necessary to analyse the sediment data in light of the hydrological and seasonal behaviour of the middle Niger River in order to determine the seasonal and sediment source effects. The data can be divided into four distinct groups, the limits of which are evident from the middle Niger River's hydrograph shown in Figure V- 29 for the Niger at Niamey. All the other stations along the middle Niger exhibit similar characteristics to varying degrees. The following four groups are distinguished in Figure V- 29:

- The rising limb of the hydrograph due to the local rainy season (1);
- The falling limb of the hydrograph that occurs at the end of the local rainy season (2);
- The rising limb of the hydrograph due to peaking of Upper Niger river that occurs in the local dry season (3);
- The falling limb of the hydrograph due to Upper Niger river (4)

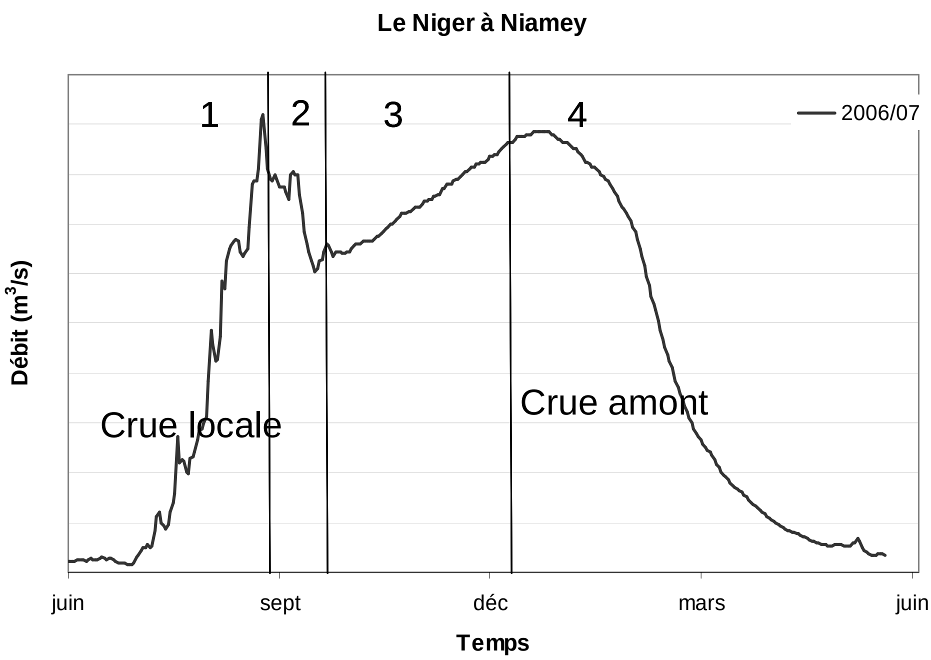
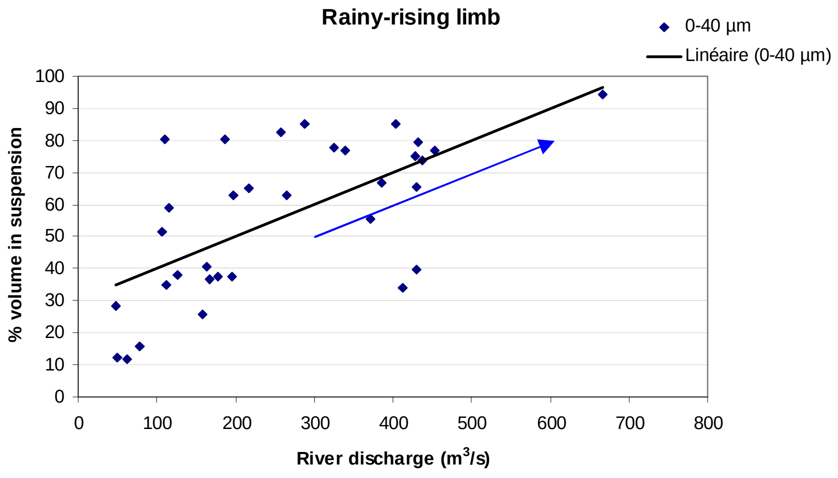
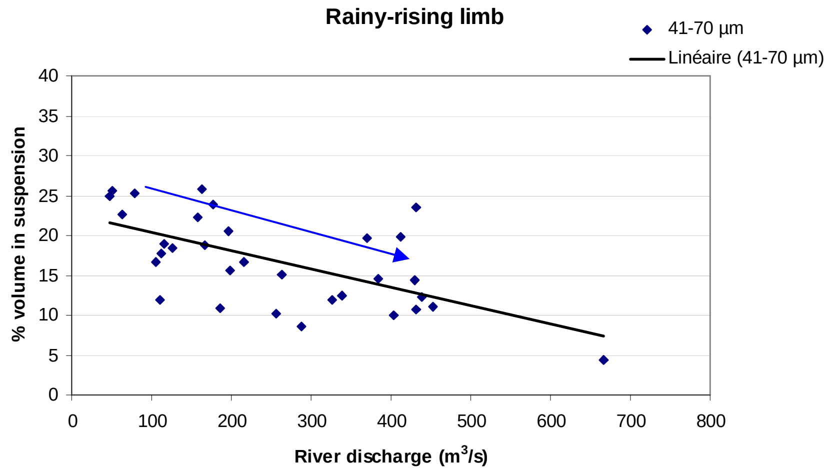
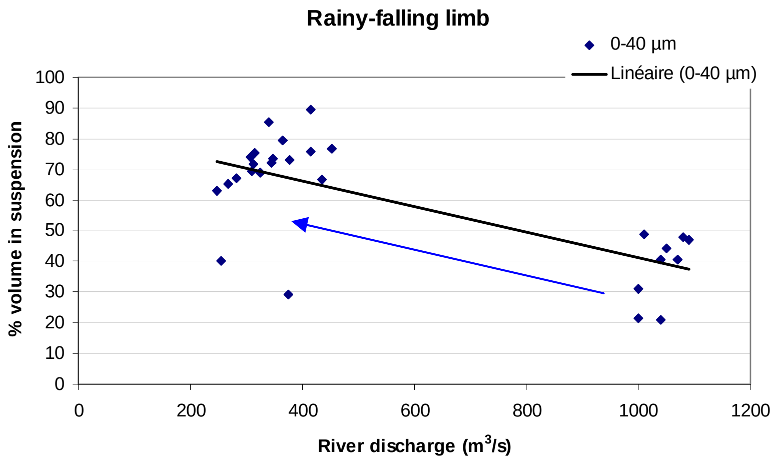


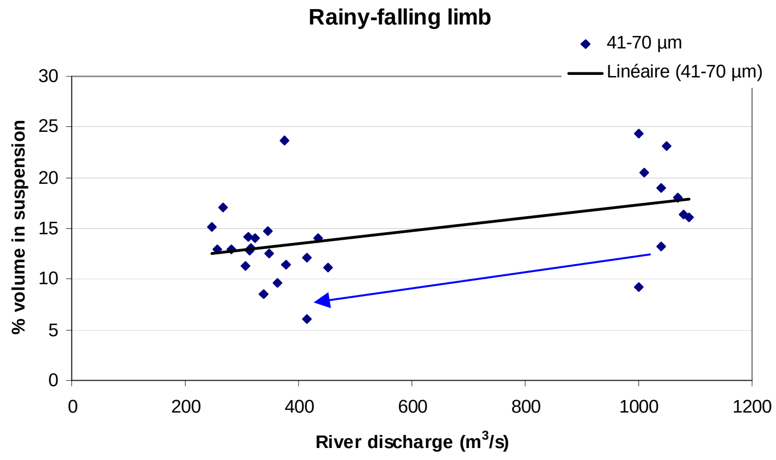
Figure V- 29: Characteristic hydrograph of the middle Niger River

The relationship between the percentage particle size in suspension and river discharge is presented in Figure V- 30. It was observed that to varying degrees, the sediment transported in suspension along the middle Niger River followed the relationship presented in Figure V- 32.


Rainy-rising limb
0-40 µm
Linéaire (0-40 µm)
% volume in suspension
River discharge (m3/s)


Rainy-rising limb
41-70 µm
Linéaire (41-70 µm)
% volume in suspension
River discharge (m3/s)


Rainy-falling limb
0-40 µm
Linéaire (0-40 µm)
% volume in suspension
River discharge (m3/s)


Rainy-falling limb
41-70 µm
Linéaire (41-70 µm)
% volume in suspension
River discharge (m3/s)

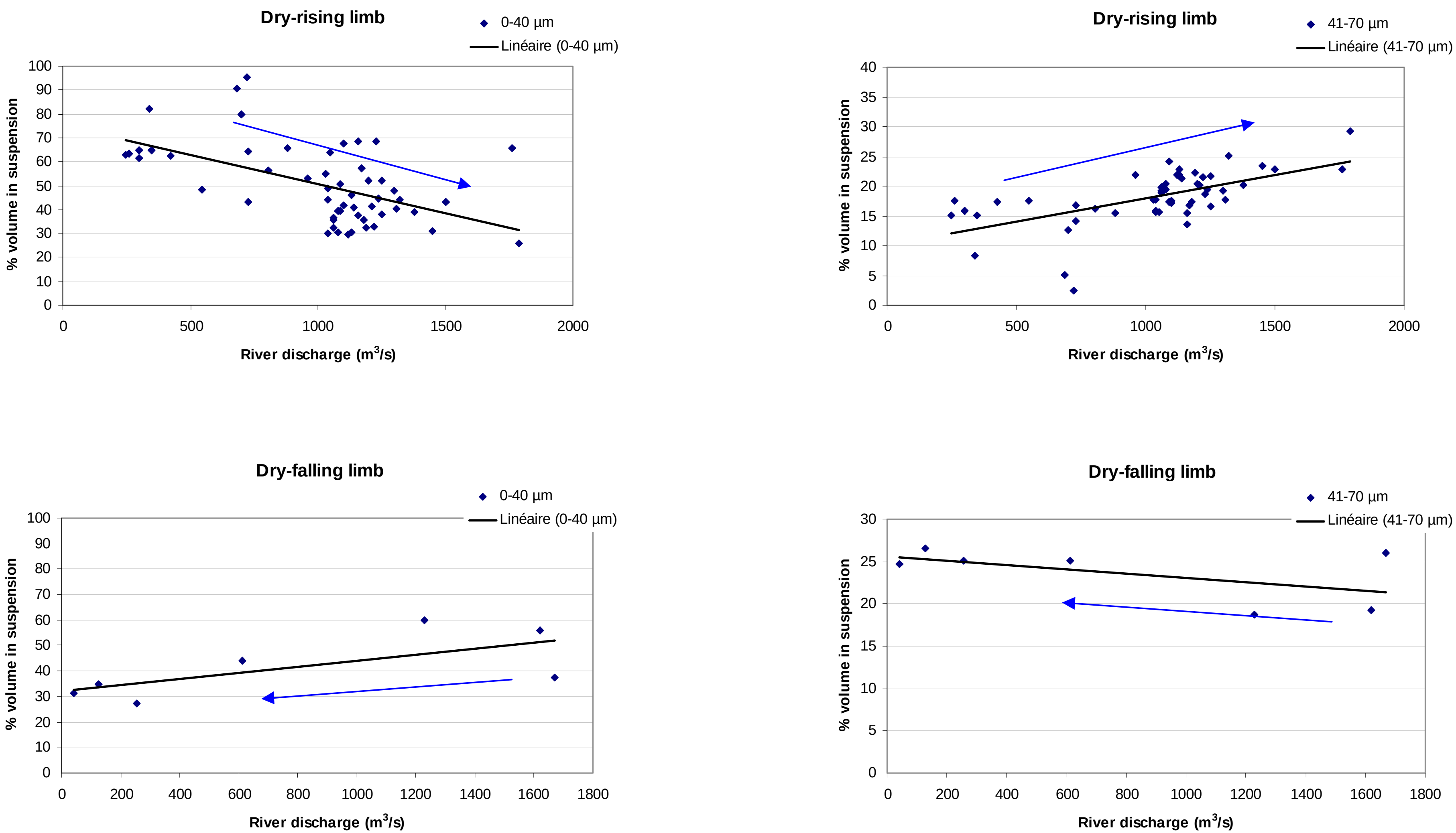


Figure V- 30: River discharge and particle size relationship for the River Niger at Kandadji

Figure V- 30 is presented only to show the general trend in the relationship between river discharge and the volume of sediment classes in suspension, as there exists a reasonable amount of scatter in some of the plots.

Two major trends were observed, one for fine sediment between 0 and 40 µm and a second trend for sediment between 41 and 70 µm. The coarser sediment from 71-1600 µm follows the trend observed for the 41-70 µm size class.

It can be noted in Figure V- 30 that as the middle Niger River's hydrograph rises during the local rainy season (June to September), the percentage of suspended sediment particles transported increases. This is because sediment fine particles, which are easily eroded, are transferred from the river's basin to the Niger. At the same time, the percentage of larger particles (41-1600 µm) in suspension decreases because more fine sediment is transported.

As the middle Niger River's hydrograph falls at the end of the rainy season, the percentage of 0-40 µm sized sediment in suspension increases. This indicates that the local rainy season discharge peak supplies mainly the 0-40 µm sediment class. As discharge and velocity reduces, the larger sizes that were also entrained by the flow settle causing an increase in the 0-40 µm class.

In the dry season as the middle Niger River's hydrograph rises for a second time (around December), the percentage of fine particles (0-40 µm) decreases and the percentage of coarse particles (41-1600 µm) in suspension increase. This is due to upstream sediment supply of coarser sediment and entrainment of coarser riverbed material.

For the falling limb of the middle Niger river‘s hydrograph (January/February), seasonal effects and the availability of sediment are the controlling factors. The percentage of 0-40 µm sized sediment decreases as discharge decreases. This is mainly because of a reduction in transfer of fine sediment to the Niger and because at high discharge even on the falling limb, the river is able to transport coarser riverbed material.

A summary of the sediment supply dynamics along the middle Niger River is presented below for the two high discharge phases of the middle Niger River.

Rising limb rainy season

- At Ayorou, the suspended sediment of 0-40 µm and 41-70 µm the size classes decrease as discharge increases during the local flood that occurs in the rainy season. The larger size classes (71-125 µm and 126-630 µm) increase with increasing river discharge. This indicates that at Ayorou sediment discharge is supply limited, as there is a deficiency of fine sediment even at the start of the rainy season.

- At Kandadji, Farié-Haoussa, Latakabiey, and Diabou-Kiria, as discharge increases during the local rainy season, the percentage by volume in suspension of the 0–40 μm size class increases. The percentage of the larger size classes in suspension decreases with increasing discharge. This indicates that fine sediment is available for transport into the Niger River around theses stations.
- The relationship is more complex for the stations at Niamey and Brigambou where the relationship between discharge and suspended sediment size is a quadratic function. As river discharge increases during the local rainy season, the percentage of sediment in the 0–40 μm class increases up to a point and then begins to decrease following a quadratic relationship with river discharge. The other size classes between 41 μm and 630 μm display the inverse relationship with discharge. This non-linearity may indicate that there are two distinct suspended sediment sources, the first source supply fine (0-40 μm) sediment, and the second source, which is transported after certain time lag providing larger sized sediment.

Rising limb dry season

- At Ayorou, Kandadji, Farié-Haoussa, Brigambou and Diabou-Kiria as river discharge increases during the second peak of the Niger River's hydrograph, the percentage volume in suspension of the 0-40 μm size class decreases. The size classes between 41 and 630 μm increase with river discharge during this phase of river discharge. This indicates that during the first peak discharge due to the local flood, the sediment deposits were mainly larger than 40 μm.
- At Latakabiey, the reverse is the case as the sediment particles between 0 and 70 μm increases as river discharge increases while the percentage of larger sediment between 71 and 630 μm reduces with increasing discharge. The discharge relationship with the size fraction between 0 and 70 μm at Latakabiey indicates that a significant amount of relatively fine particles between 0 and 70 μm were deposited between Farié-Haoussa and Latakabiey during the rainy season and are remobilized by the second discharge phase of the Niger River.
- At Niamey the percentage volume of sediment sizes less than 70 μm reduces as the river discharge increases while the percentage by volume of sediment sizes between 70 and 630 μm increases with increasing discharge.

5.4.5. Discussion of results from the middle Niger River

There exists a complex relationship between river discharge and SSC in the middle Niger River basin. This is due mainly to the variability of sediment supply in the course of a hydrological year. This is of particular significance in the middle Niger River basin where two distinct discharge peaks are observed. The semi-arid nature of the Sahelian part of the study area plays an important role in the seasonal nature of very fine sediment at the start of the rainy season. In addition to river discharge, rainfall and overland flow play an important role in the transfer of sediment to the middle Niger River.

Additionally, the size composition of sediment contributes to the variability of SSC during a hydrological year. Rainfall appears to be the major factor controlling the transfer of fine sediment to the Niger basin as observed for the two Sahelian basins. The transport of coarser particles appears to be dependent upon river discharge but also upon the percentage of fine particles already available and being transported by the river. The prediction of SSC is outside the scope of the present study, but it can be noted that any attempt at predicting suspended sediment concentration along the middle Niger River must consider the factors described above.

6. Sediment flux in the middle Niger River basin

The computation of suspended sediment discharge at a section along a river involves the approximation of suspended sediment concentration in the vertical, across the stream, and in time. For this reason, the errors that occur in estimating the sediment flux are due to the methods applied in collecting a representative sample and the interpolations that are inherent in calculating the sediment flux over a given period. This is particularly true due to the variability of daily SSC values due to the effects of rainfall, surface runoff, land use and other human influences.

6.1. Determination of the sediment flux

The instantaneous at-a-station suspended sediment load or flux can be estimated as the product of the instantaneous river discharge and the mean suspended sediment concentration in the river section. Interpolation procedures were used to estimate suspended sediment flux on the assumption that the instantaneous sample concentration is representative of the inter-sample period. Phillips et al. [1999] found that the precision of load estimates declined as sampling frequency was reduced. Errors arising from interpolation are minimized by increasing sampling frequency.

The sediment flux and annual river discharge were calculated as shown below.

Annual flood discharge (m^3): $\sum_{i=1}^{n}(Q_{mean} \times dT)$

Annual sediment discharge (g): $\sum_{i=1}^{n}(QC_{mean} \times dT)$, can be expressed in Tonnes by dividing by 10^6

Instantaneous sediment flux (g/s): $Q_i \times C_i$

Where

Q_{mean} (m^3/s): mean discharge for the period between two measurements.

dT: sampling interval (s)

Volume during sampling interval dT (m^3): Q_{mean} x dT

Q_i and C_i are the instantaneous values of discharge and suspended sediment concentration respectively at the time of sampling and n is the number of samples. QC_{mean} is the inter-sample mean sediment flux.

Other methods for calculating the sediment flux have been described elsewhere [*N Filizola*, 2003; *G Lienou*, 2007].

6.2. Sediment flux along the middle Niger River

In the 2006/07 water year, sampling at the stations along the Niger River only continued up to October 2007, except for the Niamey station where sampling continued throughout the year. Total water discharge at Niamey for the 2006/07 season was 29.1 billion m^3 and the sediment flux was 10.35 million tonnes (calculated using single sample SSC values) or 11.66 million tonnes (using the corrected cross-sectional values). The sediment flux along the middle Niger River will be discussed in terms of the corrected cross-sectional values.

From June to October of the 2007/08 season, sediment sampling was done on a daily basis, while the sampling frequency was reduced to 3-day intervals for the rest of the year. The cumulative river discharge and annual sediment flux at each station along the Niger River are presented in Table V- 6 and include the values measured at Niamey in the 2006/07 water year.

The cumulative annual river discharge increases in the direction of the river flow except for the Niamey-Brigambou area. The water deficit between Niamey and Brigambou can be attributed to the amount of water abstracted for domestic, agricultural, and limited industrial use in Niamey. According to FAO [*FAO*, 1997], the Niger River and its tributaries provide about 90% of the water demand of the Niger republic. Davis [*T Davis*, 2003] estimated that the agricultural water demand in the Niger River basin within the republic of Niger (the middle Niger) is about 1.89 billion cubic metres per year.

Table V- 6: Sediment flux of the middle Niger River

Station	Distance from nearest upstream station (km)	Period	Water Discharge ($10^9 m^3$/year)	Sediment flux (10^6 Tonnes/year)	
				Single sample	Cross-sectional estimate
Ayorou	-	2007/08	incomplete	incomplete	-
Kandadji	13	2007/08	24.904	11.67	12.68
Farié-Haoussa	105	2007/08	25.132	11.74	12.74
Latakabiey	5	2007/08	26.898	12.36	13.50
Niamey	53	*2006/07*	*29.104*	*10.41*	*11.84*
		2007/08	29.978	15.19	16.36
Brigambou	167	2007/08	26.486	10.03	11.17
Diabou-Kiria	15	2007/08	29.185	10.10	11.44

Table V- 6 shows that sediment discharge increases along the Niger River in the flow direction reaching a maximum at Niamey.

As at the time sampling stopped at Ayorou (04/10/2007), 1.91 million tonnes of sediment had been measured at Ayorou and 2.92 million tonnes of sediment had been transported by the Niger at Kandadji.

Between Kandadji and Farié-Haoussa, the sediment flux increases only slightly indicating that the Niger River does not receive significant sediment input along the Kandadji-Farié Haoussa stretch. The increase in sediment flux between Farié-Haoussa and Latakabiey is largely due to the sediment input of the Sirba River. The greatest increase in sediment flux between any two stations occurs between Latakabiey and Niamey. The Niger between these two stations does not receive any major tributary, but as discussed in part II of this work receives numerous ungauged ephemeral streams. A reduction in the sediment flux occurs along the middle Niger River between Niamey and Brigambou by about 5 million tonnes per year. This amount of sediment that is not transferred from Niamey to Brigambou may be deposited in the riverbed (for large particles) or may be exiting the system by overland deposition.

Between the 2006/07 water year and the 2007/08 water year, the sediment transiting at Niamey increased from about 11.84 million tonnes/year to over 16 million tonnes/year with only a slight increase in the cumulative river discharge.

The specific fluxes (flux per basin area) show similar trends, see Table V- 7.

Table V- 7: Specific sediment flux along the middle Niger River

Station	Basin area (km²)	Période	Annual flux (million T)	Specific flux (T/km²)
Kandadji	628 830	2007/08	12.68	20.2
Farié-Haoussa	650 380	2007/08	12.74	19.6
Latakabiey	689 130	2007/08	13.50	19.6
Niamey	700 000	2006/07	11.84	16.9
		2007/08	16.36	23.4
Brigambou	736 250	2007/08	11.17	15.2
D-Kiria	757 640	2007/08	11.44	15.1

It is to be noted that the Niamey measuring station was located downstream of the water retaining sill at Goudel, therefore the deficit in sediment between Niamey and Brigambou is not due to sediment trapping or settling in this reservoir.

Between Brigambou and Diabou-Kiria, there is a slight increase in sediment flux largely due to the Mékrou River. Based on the sediment flux calculated upstream and downstream of the Sirba and the Mékrou rivers, it can be noted that the sediment input to the Niger River by the Sirba River (about 800,000 tonnes/year) is almost three times that of the Mékrou River (about 270,000 tonnes/year).

6.3. Sediment flux in the tributaries

The sediment flux values calculated for the two Sahelian basins during the study period are presented in Table V- 8. An increase in water discharge between the two seasons occurred in the two basins during the study period.

Table V- 8: Sediment flux of the Gorouol and Sirba Rivers

Station	Period	Water Discharge($10^9 m^3$/year)	Sediment flux (10^6 Tonnes/year)
Alcongui	2006/07	0.814	0.476
	2007/08	0.963	1.097
Tiambi	2006/07	0.810	0.497
	2007/08	1.650	0.853
Garbé-Kourou	2006/07	0.848	0.587
	2007/08	1.701	1.332

The Gorouol discharged about 814 and 963 million cubic metres of water in the 2006/07 and 2007/08 water years respectively. For the same periods, the Sirba at Garbé-Kourou discharged 848 million cubic metres and 1.7 billion cubic metres of water. In comparison to the Sahelian basins, the Mékrou at Barou (near the Mékrou-Niger confluence) discharged about 2.65 billion cubic metres in the 2006/07 year.

The increased volume of water discharged resulted in an increase in the sediment discharge in the two Sahelian basins during the study period. For the two seasons, the water and sediment discharged by the Sirba was higher than volume of water and mass of sediment discharged by the Gorouol. Although suspended sediment was not measured on the Mékrou River, the relatively small increase between sediment discharge at Brigambou and Diabou-Kiria indicate that although the Mékrou discharges more water to the River Niger than the Sirba does, the sediment input from the Mékrou is relatively low.

The specific fluxes are presented in Table V- 9 showing the same trend described by the sediment flux in Table V- 8.

Table V- 9: Specific sediment fluxes of the Gorouol and Sirba Rivers

Station	Basin area (km^2)	Période	Annual flux (million T)	Specific flux (T/km^2)
Alcongui (Gorouol)	44 450	2006/07	0.476	10.7
		2007/08	1.097	24.7
Tiambi (Sirba)	37 370	2006/07	0.497	13.3
		2007/08	0.855	22.9
G-Kourou (Sirba)	38 704	2006/07	0.582	15.2
		2007/08	1.332	34.4

6.4. Change in sediment flux in the course of a water year

A graphical representation of the evolution of sediment flux along the middle Niger River for 2007/08 is presented in Figure V- 31. (Sediment flux was not calculated for the Niger River at Ayorou because of incomplete data)

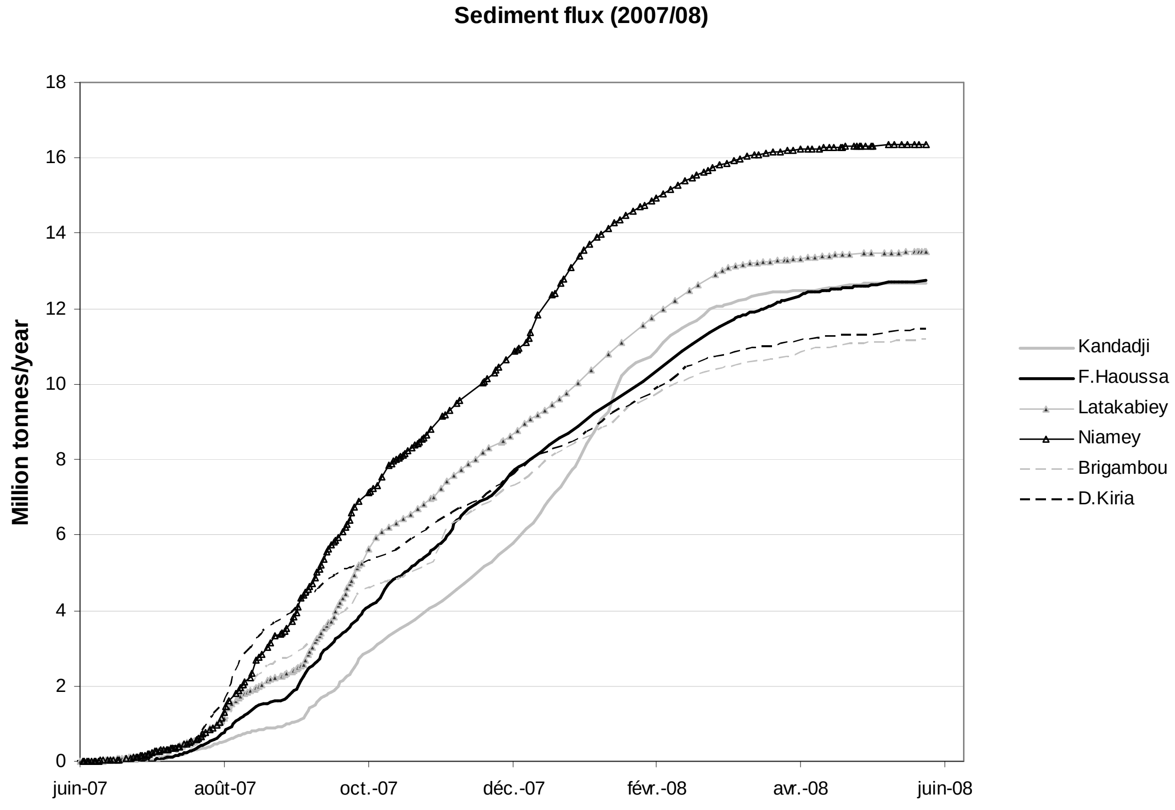
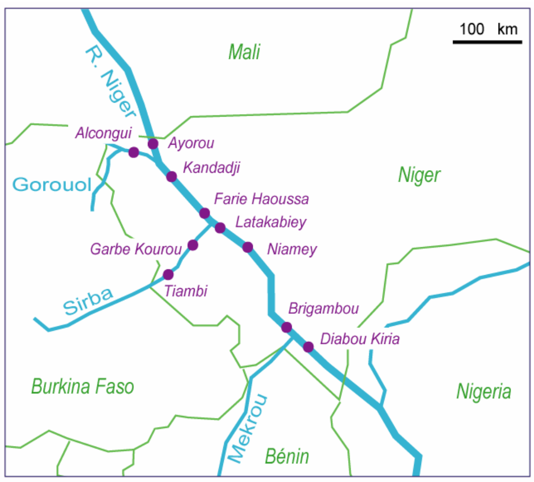


Figure V- 31: Sediment flux along the middle Niger River 2007/08

Figure V- 31 indicates the sediment flux is uniform along all the stations along the middle Niger in June. By the end of July, the amount of sediment passing Farié-Haoussa begins to increase in comparison to sediment discharged at Kandadji. This could be due to sediment input from a source (like the interior delta) or a smaller tributary upstream of Kandadji. The sediment that can be seen to transit from Kandadji between February and April could be said to be due to the remobilization of stored sediment at high river discharge and low sediment supply from the basin.



At the Sirba-Niger confluence between Farié-Haoussa and Latakabiey, the difference in sediment flux at the two stations begins to increase in July and reaches a maximum in October. This first phase of sediment surplus between Farié-Haoussa and Latakabiey can be said to be due mainly to sediment input from the Sirba River. The difference in sediment flux is maintained until May, which may signify the transport of sediment deposited in the riverbed between Farié-Haoussa and Latakabiey.

Between Latakabiey and Niamey, the departure in the amount of sediment transported past the two stations occurs in August at the height of the middle Niger's discharge peak due top the local rainy season. From then on, the amount of surplus sediment discharged past Niamey continues to increase, attaining about 2.8 million tonnes more than the sediment transported past Latakabiey for the 2007/08 water year. This excess sediment can be attributed to ephemeral streams and gullies that occur between Latakabiey and Niamey in addition to the transportation of riverbed material.

The sediment flux between Niamey and Brigambou is only uniform until August, when large amounts of sediment transported past Niamey do not reach Brigambou.

At the Mékrou-Niger confluence between Brigambou and Diabou-Kiria, the difference in sediment flux begins to increase in July reaching a peak in September due mainly to sediment input from the Mékrou River.

6.5. Discussion

Previous suspended sediment measurements along the middle Niger River (see Table V- 4) reported that the sediment flux at Kandadji ranged between 1.3 and 2 million tonnes/year at Kandadji and between 3.1 and 3.9 million tonnes/year at Niamey. The present study has shown that by excluding fine sediment less than about 10 μm, sediment concentration values and thus sediment flux may have been underestimated by up to 25% on average using the same field sampling method. Furthermore, the improved sampling frequency applied to this study particularly during the rainy season may have resulted in a better estimation of the sediment characteristics of the middle Niger River with respect to the previous sampling program. It is difficult to compare the results of the two sampling programs for these reasons even though it is tempting to expect that some of the "surplus" sediment measured during this study may be due to increased basin erosion.

Although the sampling period was for a maximum period of two complete hydrological years, the results obtained represent a reasonably accurate quantification of the sediment flux along the middle Niger River. The estimated specific sediment yield value of 26 tonnes/km^2/year for the Niger River basin put forward by Ludwig and Probst [1998] closely approximate the results obtained considering a basin area of 700,000 km^2 at Niamey translates to a sediment discharge of 18.2 million tonnes/year.

The results indicate that as the Niger crosses the Sahel, the suspended sediment flux increases and reaches a maximum around Niamey. The sharp increase in sediment flux between Latakabiey and Niamey in the absence of conventional tributaries between these two stations indicates that there exist other significant sediment sources on the Latakabiey-Niamey stretch of the Niger River. The reduction in sediment discharge between Niamey and Brigambou indicate that between these two stations in-channel or overbank deposition occurs. The results also indicate that even with higher river discharge the Sudanian Mékrou River transports less sediment to the Niger River than the Gorouol and Sirba rivers.

7. Comparison of simulated sediment transport capacity with measured SSC

In order to gain a better understanding of the fundamental processes and phases of sediment transport in the middle Niger River it was necessary to carry out a simulation of the sediment transport capacity of that stretch of the Niger River.

Van Rijn [1993] presented a sediment transport formula to calculate the sediment transport capacity by combining river channel hydrodynamic parameters with riverbed material characteristics. The transport capacity for suspended load was calculated using measured riverbed sediment data and hydrodynamic data obtained from the CARIMA model of the Niger River from Kandadji to Diabou-Kiria using the following formula:

Suspended sediment concentration $c = c_a\left[\left(\frac{h-Z}{Z}\right)\left(\frac{k_s}{h-k_s}\right)\right]^Z$ **(kg/m³)**

Reference concentration $c_a = 0.015 * \frac{D_{50}}{k_s} * \frac{T^{1.5}}{D_*^{0.3}} * \rho_s$ **(kg/m³)**

Suspension number $Z = \omega_s / (\beta \kappa u_*)$

Particle parameter: $D_* = D_{50}\left[\frac{(s-1)g}{\nu^2}\right]^{1/3}$

Grain related Chézy coefficient: $C' = 18\log\left(12h / 3D_{90}\right)$ **(m^1/2^/s)**

Current related effective bed shear stress: $\tau'_b = \rho g \left(\bar{u} / C'\right)^2$ **(N/m²)**

Shields critical bed shear stress τ_{bcr} **(N/m²)**

When

$$
\begin{aligned}
&1 < D_* \le 4 \Rightarrow \tau_{bcr} = 0.24 D_*^{-1}(\rho_s - \rho) g D_{50} \\
&4 < D_* \le 10 \Rightarrow \tau_{bcr} = 0.14 D_*^{-0.64}(\rho_s - \rho) g D_{50} \\
&10 < D_* \le 20 \Rightarrow \tau_{bcr} = 0.04 D_*^{-0.1}(\rho_s - \rho) g D_{50} \\
&20 < D_* \le 150 \Rightarrow \tau_{bcr} = 0.013 D_*^{0.29}(\rho_s - \rho) g D_{50} \\
&D_* > 150 \Rightarrow \tau_{bcr} = 0.055(\rho_s - \rho) g D_{50}
\end{aligned}
$$

Bed shear stress parameter: $T = \left(\frac{\tau'_b - \tau_{bcr}}{\tau_{bcr}}\right)$

Representative particle size of suspended sediment D_s (m)

$$D_s = [1 + 0.011(\sigma_s - 1)(T - 25)]D_{50}$$
$$when$$
$$T \geq 25, \Rightarrow D_s = D_{50}$$

Particle fall velocity ω_s (m/s)

$$1 < D_s \leq 100\mu m \Rightarrow \omega_s = \frac{(s-1)gD_s{}^2}{18\nu}$$
$$100 < D_s \leq 1000\mu m \Rightarrow \omega_s = 10\frac{\nu}{D_s}\left\{\left[1 + \frac{0.01(s-1)gD_s{}^3}{\nu^2}\right]^{0.5} - 1\right\}$$
$$D_s > 1000\mu m \Rightarrow 1.1[(s-1)gD_s]^{0.5}$$

Effective bed roughness k_s (m)

When $100 \leq D_{90} \leq 600\mu m; \Rightarrow k_s = 5.1D_{84}$
$1000 \leq D_{90} \leq 20000\mu m; \Rightarrow k_s = 2.3D_{84}$

In which,

ρ **= fluid density (1000 kg/m^3)**

ρ_s **= sediment density (2650 kg/m^3)**

s= specific density $= \left(\rho_s / \rho\right)$

ν **= kinematic viscosity coefficient (m^2/s) [*assuming a water temperature of 20°C*]**

h= flow depth (m)

D_{50} **= median particle diameter of bed material (m)**

D_{16}, D_{84}, D_{90} **= characteristic diameter of bed material (m)**

$\sigma_s = \frac{1}{2}\left(\frac{D_{84}}{D_{50}} + \frac{D_{50}}{D_{16}}\right)$ **Geometric standard deviation of bed material**

u_* **= bed shear velocity (m/s)**

κ **= von Karman's constant (=0.4)**

$\beta = 1 + 2\left(\omega_s / u_*\right)^2$ **Ratio of sediment and fluid mixing coefficients**

g= acceleration due to gravity (=9.81 m/s^2)

In order to compare the sediment transport capacity to measure suspended sediment values, the transport capacity for four classes found in the riverbed and in suspension was computed. The four sediment size classes were 41-70 µm, 71-125 µm, 126-630 µm and 630-1600 µm. This was achieved by calculating the sediment transport capacity assuming the bed was made up solely of the class mark of each sediment size class in order to attain the maximum amount of sediment transportable.

The results obtained for the period between June 2006 and May 2008 indicate the maximum amount of transportable sediment concentration for each size class. In other words, when sediment concentration is above the sediment transport capacity, deposition occurs. On the other hand, sediment concentrations below the sediment transporting capacity for each class are transported downstream.

The rate of sediment deposition was calculated as:

$$D = \left(1 - C_p / C_m\right) C_m \times \omega$$

Where D is the rate of sediment deposition per unit area (kg/s/m²)

C_p = Potential suspended sediment concentration (kg/m^3)

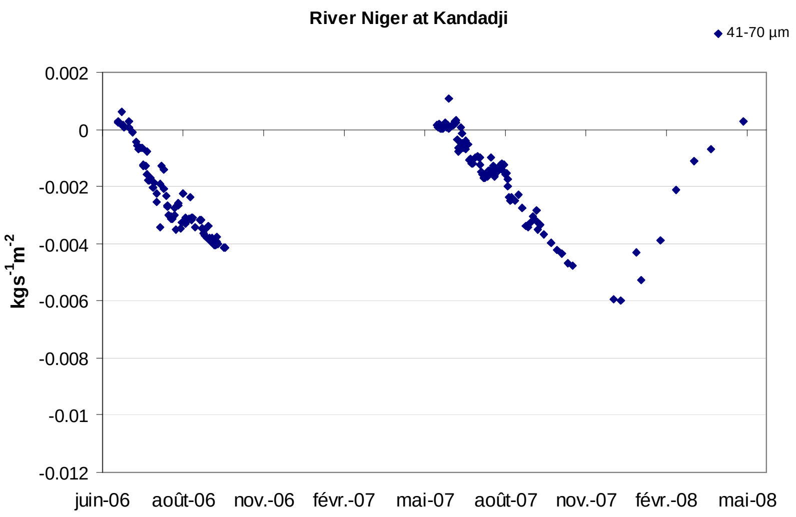
C_m = Measured suspended sediment concentration (kg/m^3)

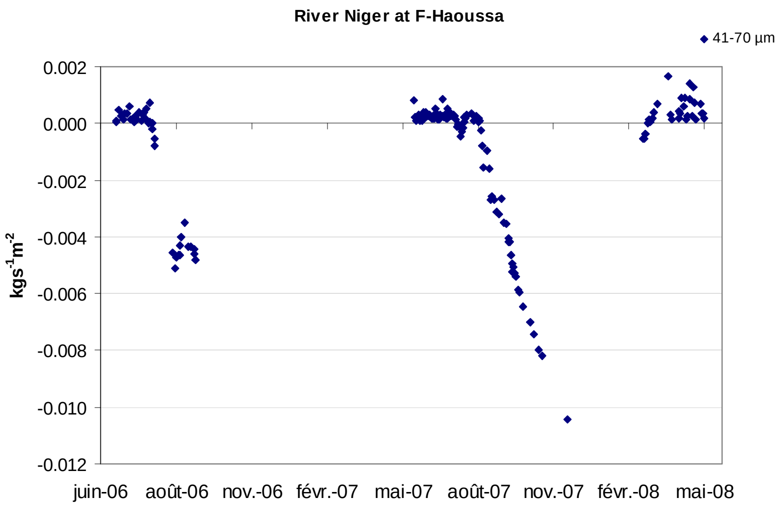
ω = sediment fall velocity (m/s)

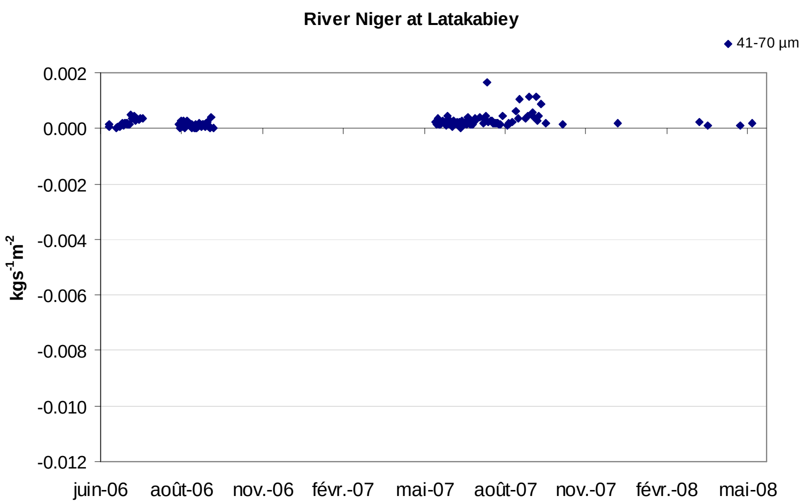
7.1. Presentation of results

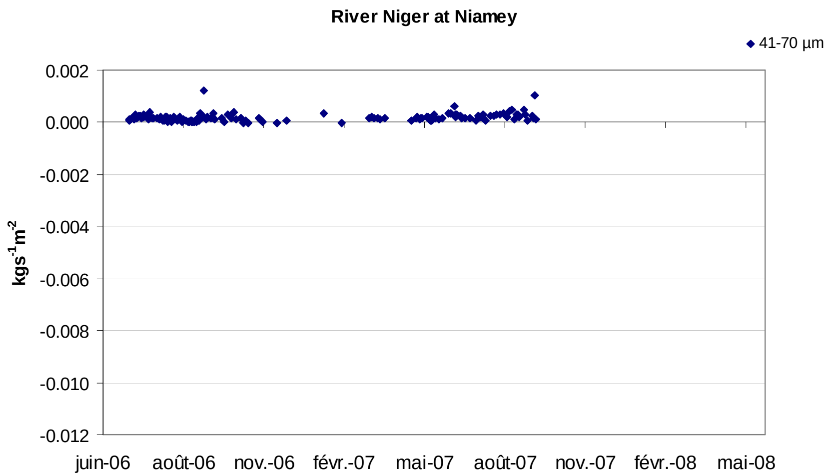
The results obtained are compared for the sediment transport capacity of sediment size classes ranging from 41 µm to 1600 µm with measured values. The range of sediment sizes between 41 µm and 1600 µm represent the sediment sizes found both in the riverbed material and in suspension. Values on the y-axis are positive when measured values are greater than the calculated sediment transport capacity, leading to deposition. Y-axis values are negative when the calculated sediment transport capacity is larger than the measured suspended sediment concentration value.

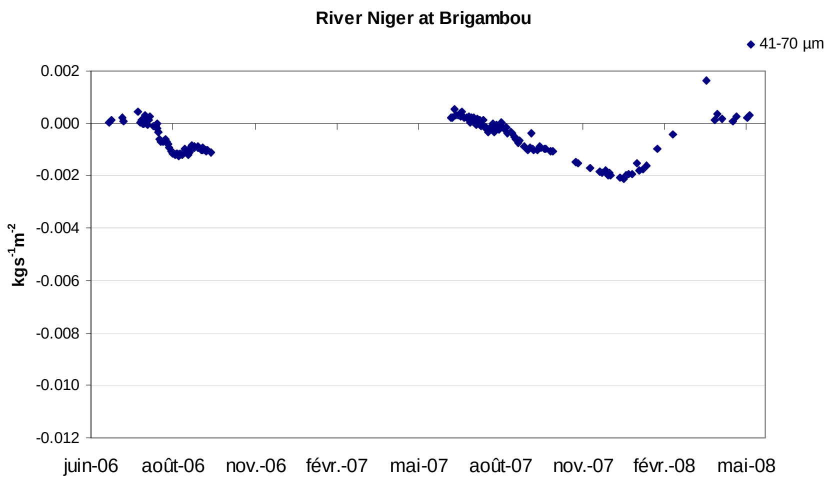
- Figure V- 32 indicates that at Kandadji, Farié-Haoussa and Brigambou, suspended sediment of the 41-70 µm size are transported downstream most of the time except at very low river discharge that occurs between May and June. For the other stations (Latakabiey, Niamey and Diabou-Kiria, low amounts of the 41-70 µm sediment class are not transported downstream but deposited.


River Niger at Kandadji
41-70 µm
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
kgs-1m-2
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08


River Niger at F-Haoussa
41-70 µm
0.002
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
-0.012
kgs-1m-2
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08


River Niger at Latakabiey
41-70 µm
0.002
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
-0.012
kgs-1m-2
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08


River Niger at Niamey
41-70 µm
0.002
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
-0.012
kgs-1m-2
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08



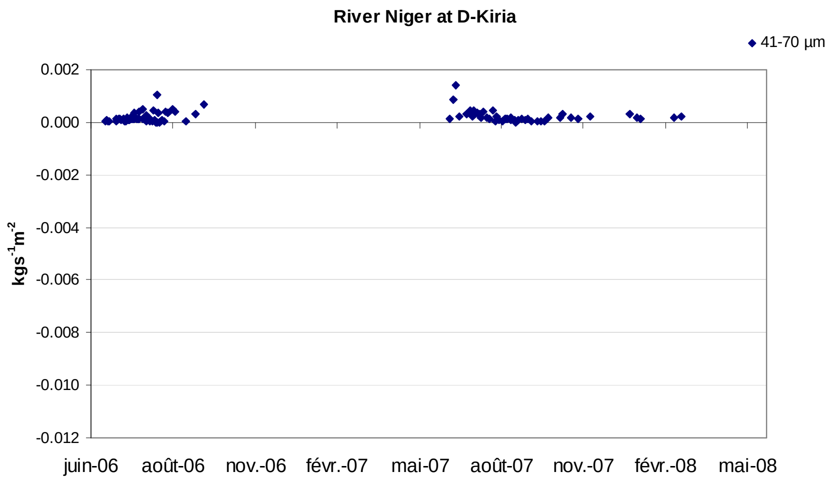
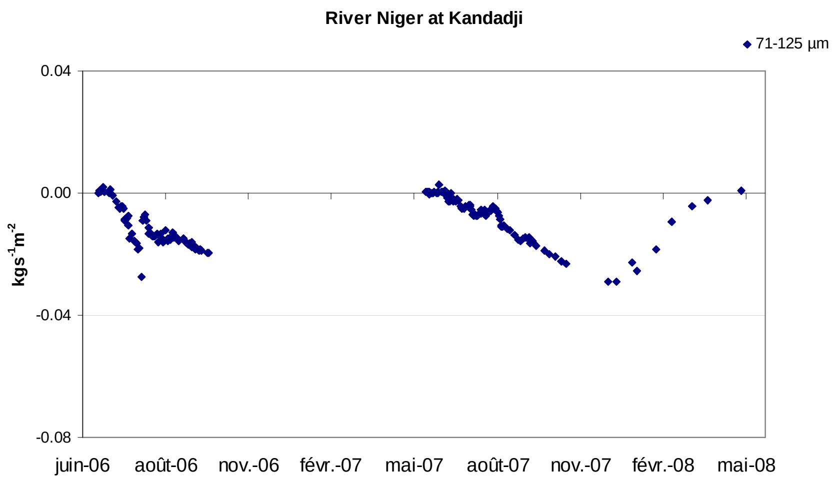
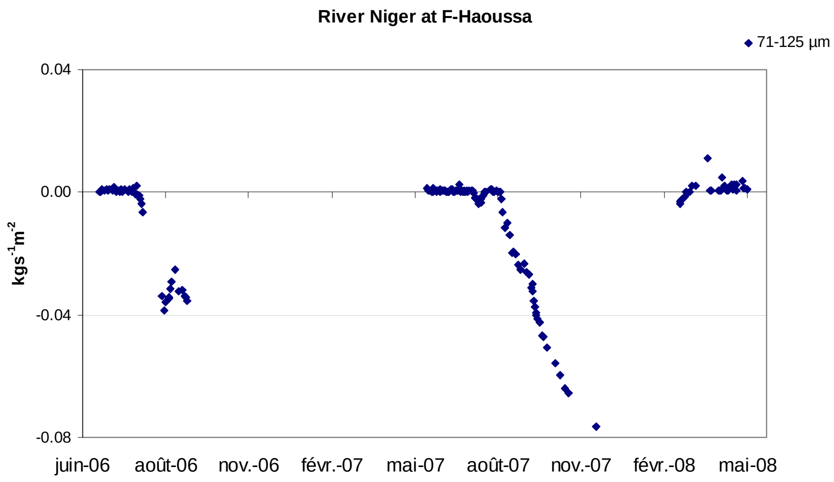
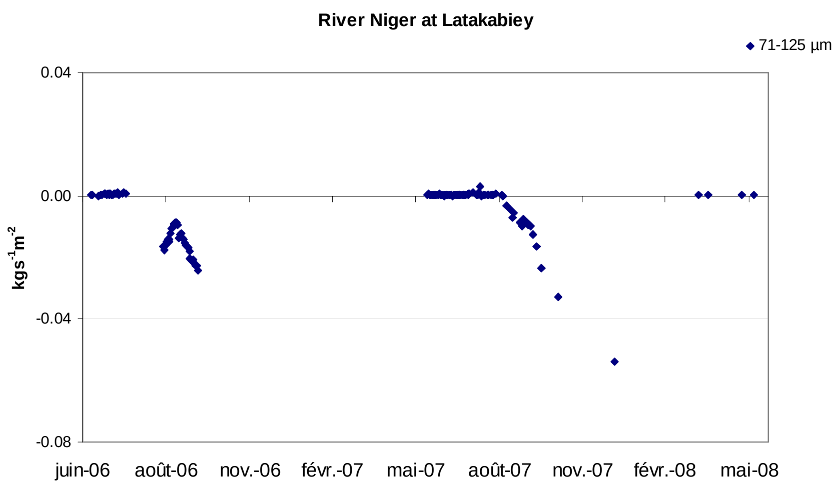


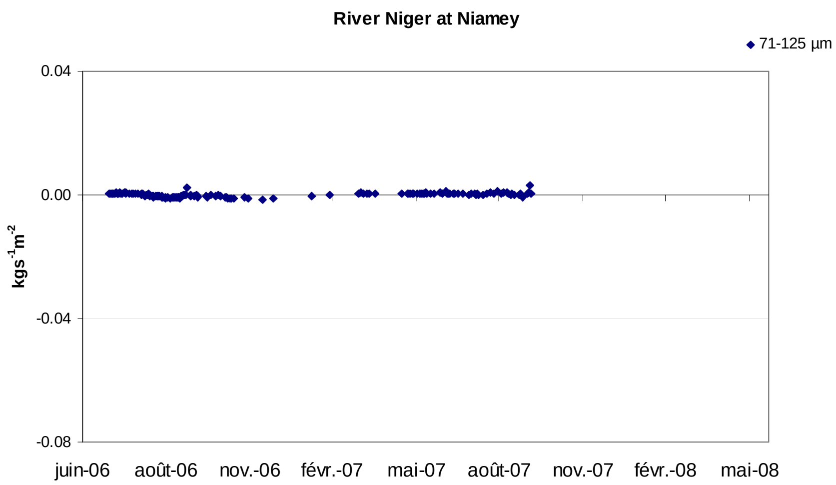
Figure V- 32: Deposition trend of suspended sediment (41-70 µm) for the middle Niger River

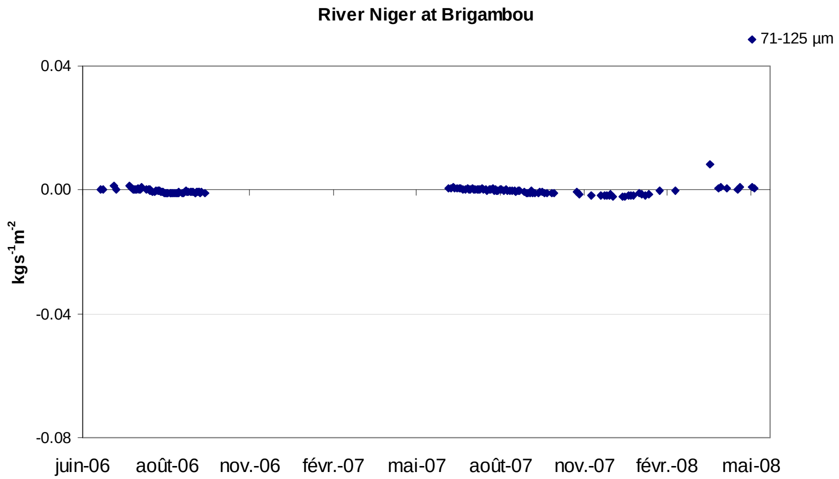
- For the sediment class consisting of particles between 71 μm and 125 μm, very low amounts of sediment are deposited at the start and end of the hydrological year but are largely transported at Kandadji, Farié-Haoussa and Latakabiey. Between September and March, the Niger River at Latakabiey transports sediment between 71 and 125 μm. This is because the amount of this class in suspension between September and March is less than the amount in the 41 to 70-μm size class. A second reason for this occurrence is that due to size composition of the riverbed material at Latakabiey, the transporting capacity for the 71 to 125-μm size class is much higher than that for the 41 to 70 μm size class. At the other stations, the net transport or deposition of this size class is close to zero.
- For the sediment class consisting of particles between 126 μm and 630 μm, deposition occurs at Kandadji and Farié-Haoussa between June and September. The sediment of this size class is transported between October and February.
- For the sediment class consisting of particles between 631 μm and 1600 μm, Figure V- 35 shows that at all stations, this size class is deposited.


River Niger at Kandadji
71-125 µm
0.04
0.00
-0.04
-0.08
kgs-1m-2
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08


River Niger at F-Haoussa
71-125 µm
0.04
0.00
-0.04
-0.08
kgs-1m-2
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08


River Niger at Latakabiey
71-125 µm
0.04
0.00
-0.04
-0.08
kgs-1m-2
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08


River Niger at Niamey
71-125 µm
0.04
0.00
-0.04
-0.08
kgs-1m-2
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08



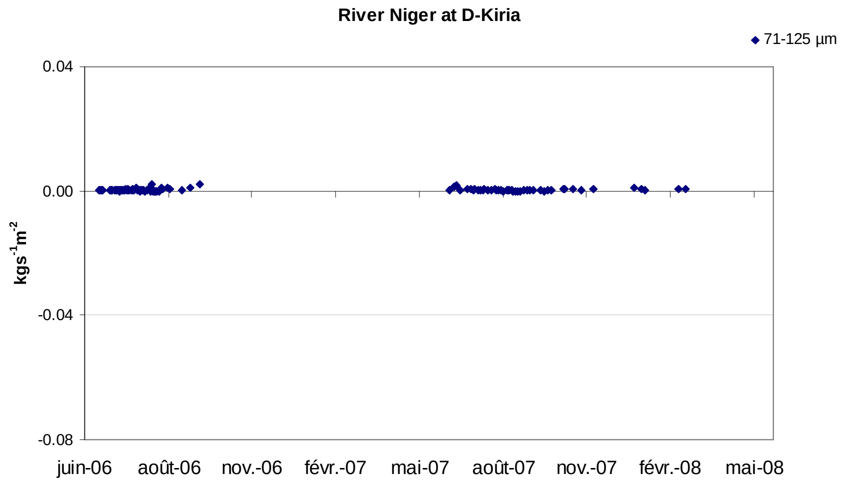
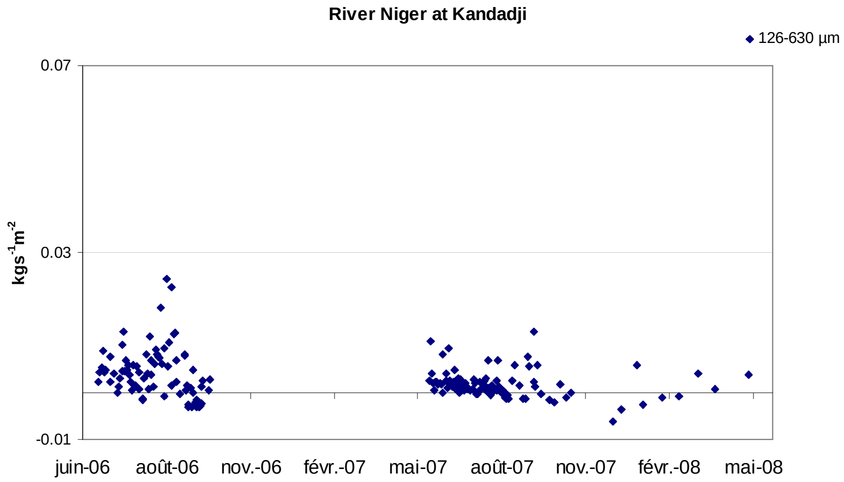
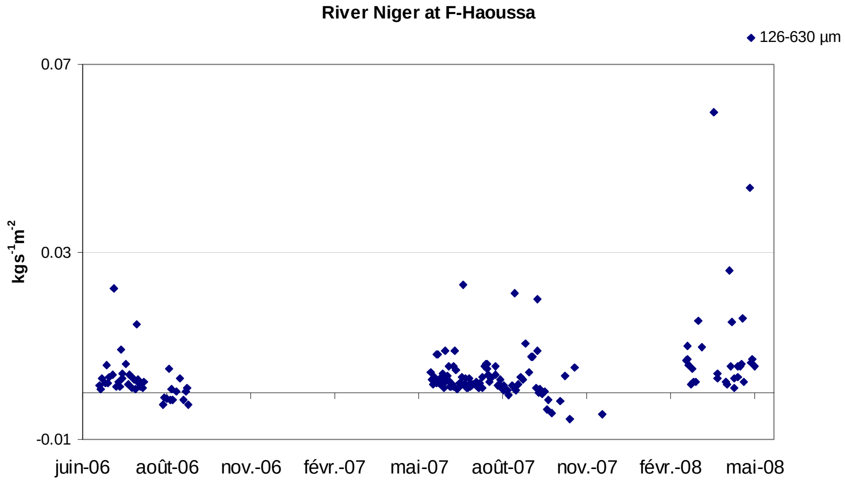
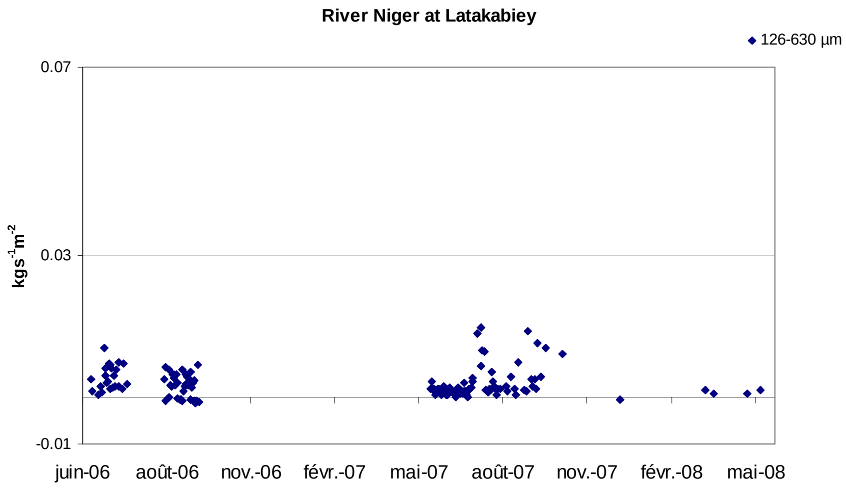
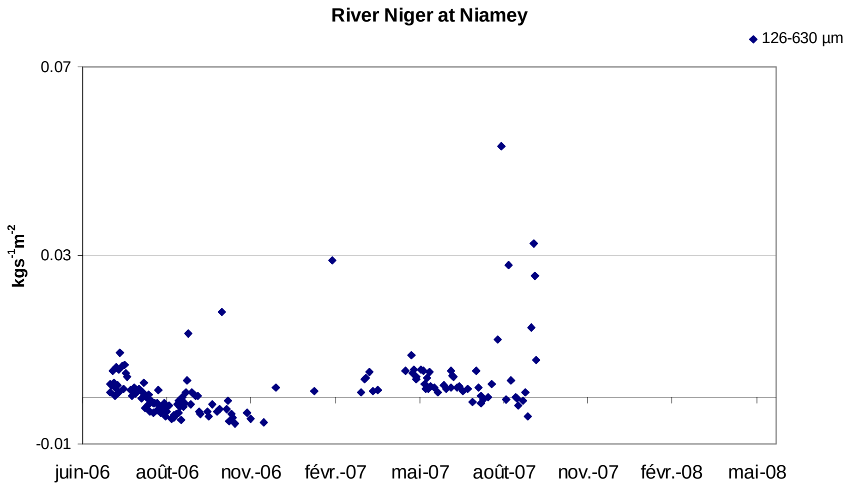


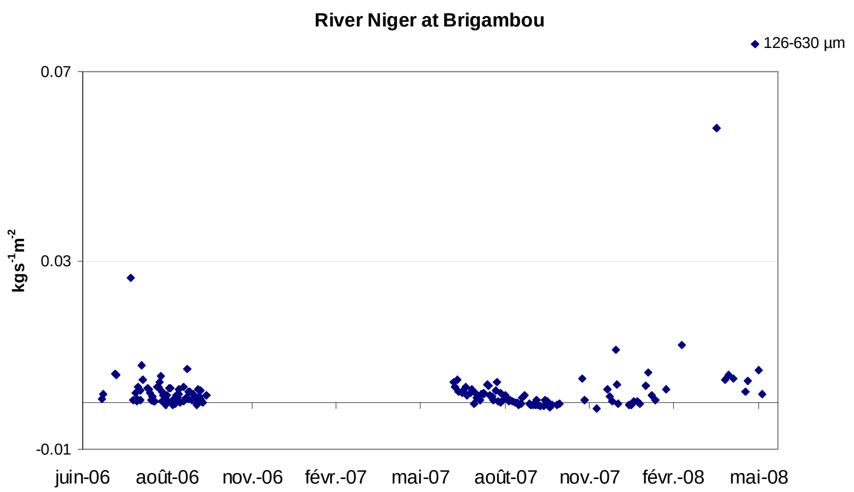
Figure V- 33: Deposition trend of suspended sediment (71-125 µm) for the middle Niger River


River Niger at Kandadji
126-630 µm
kgs-1m-2
0.07
0.03
-0.01
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08


River Niger at F-Haoussa
126-630 µm
kgs-1m-2
0.07
0.03
-0.01
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08


River Niger at Latakabiey
126-630 µm
kgs-1m-2
0.07
0.03
-0.01
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08


River Niger at Niamey
126-630 µm
kgs-1m-2
0.07
0.03
-0.01
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08



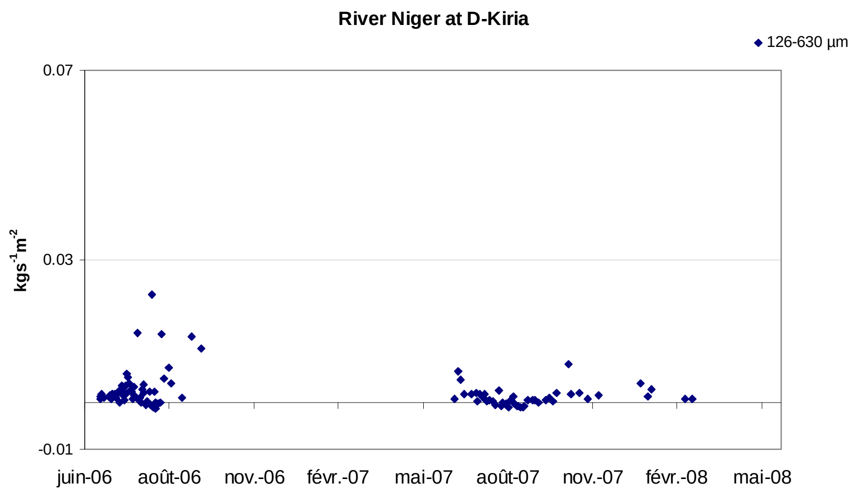
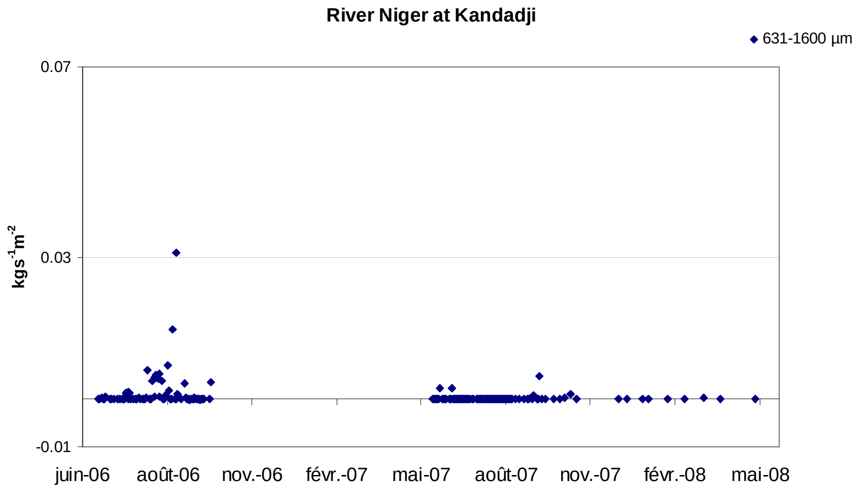
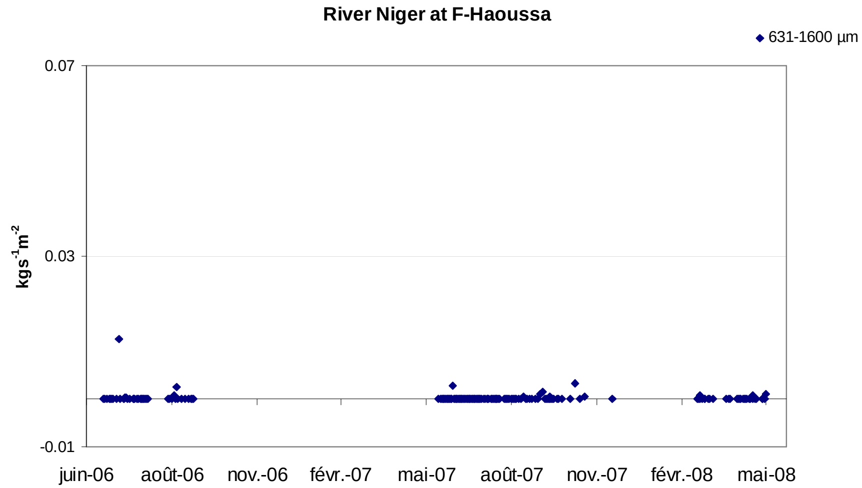
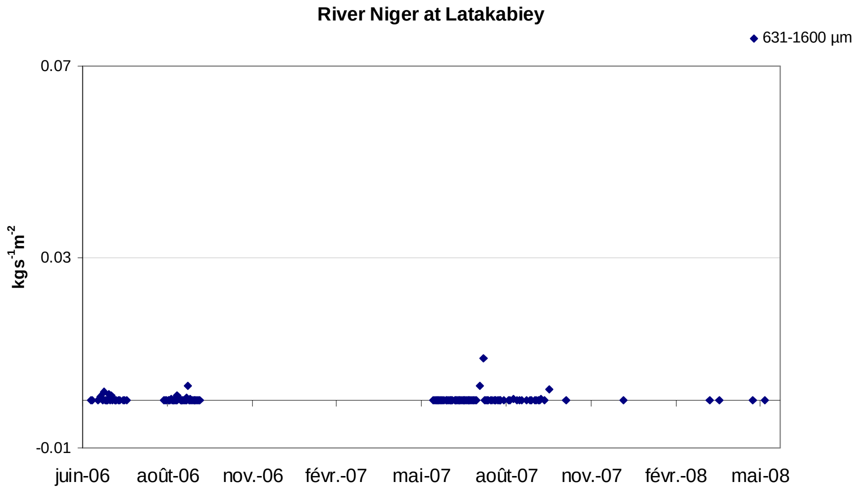
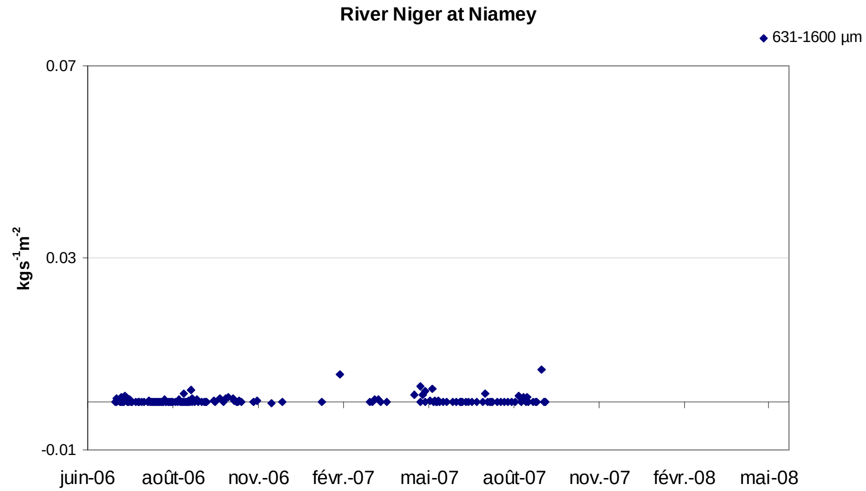


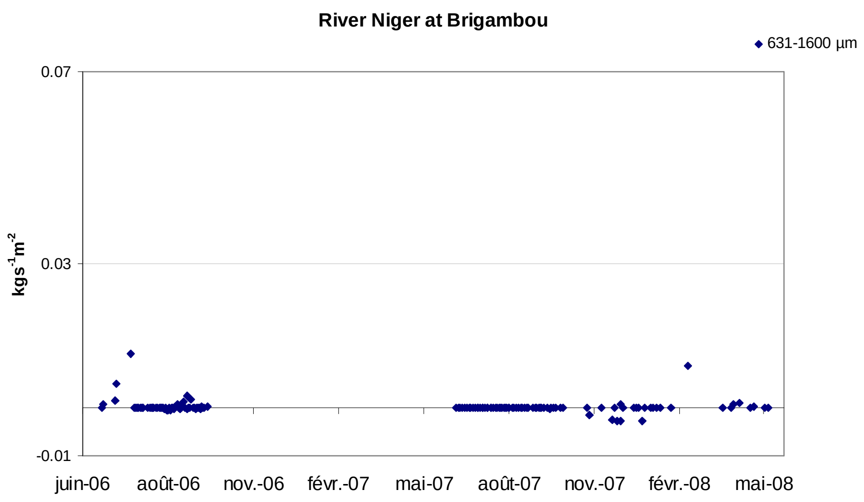
Figure V- 34: Deposition trend of suspended sediment (126-630 µm) for the middle Niger River


River Niger at Kandadji
631-1600 µm
kgs-1m-2
0.07
0.03
-0.01
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08


River Niger at F-Haoussa
631-1600 µm
kgs-1m-2
0.07
0.03
-0.01
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08


River Niger at Latakabiey
631-1600 µm
kgs-1m-2
0.07
0.03
-0.01
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08


River Niger at Niamey
631-1600 µm
kgs-1m-2
0.07
0.03
-0.01
juin-06
août-06
nov.-06
févr.-07
mai-07
août-07
nov.-07
févr.-08
mai-08



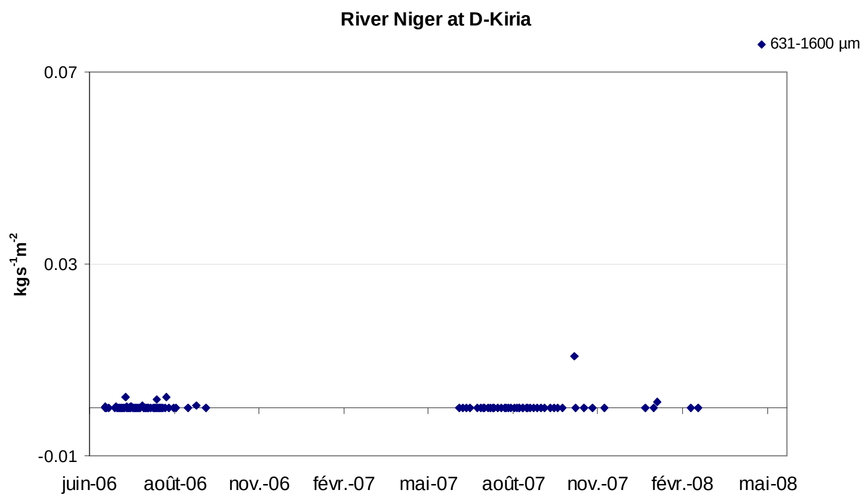


Figure V- 35: Deposition trend of suspended sediment (631-1600 µm) for the middle Niger River

7.2. Seasonal sediment transfer dynamics

The sediment transport dynamics for the stretch from Kandadji to Diabou-Kiria on the Niger River is described for four periods of the water year. The periods are the low flow period, the high discharge period due to the local rainy season, the high discharge period due to delayed upstream discharge and the falling limb of the hydrograph, corresponding to June, September, December, and March respectively. In Figure V- 36 to Figure V- 39, positive values indicate deposition while negative values represent transport of the sediment class in suspension.

- Figure V- 36 shows the sediment transport dynamics of sediment in the 41-70 μm size range. In general, at low flows occurring in June sediment of the 41-70 μm are deposited because the transport capacity at all stations along the middle Niger River are not high enough to keep the sediment in suspension. In September, at the peak discharge due to the local rainy season, the 41-70 μm class is transported past Kandadji, Farié-Haoussa and Brigambou, but is deposited at Latakabiey, Niamey and Diabou-Kiria. At peak discharge in December, the Niger River transports the sediment in the 41-70 μm class at all the stations except for low-level deposition occurring at Latakabiey and Diabou-Kiria. In March as the river discharge decreases, sediment of the 41-70 μm size class is deposited at Farié-Haoussa, Latakabiey, Niamey, and Diabou-Kiria.

- Figure V- 37 describes the sediment transfer dynamics for sediment of 71-125 μm size class. Low flows in June do not sustain the transport by suspension of sediments in the 71-125 μm size class at any of the stations along the middle Niger River. In September, the Niger River sustains this size class in suspension at all stations except at Niamey and Diabou-Kiria. In December as river discharge reaches a maximum, the Niger transports all sediment of the 71-125 μm size class at all stations along the middle Niger River. In March, as observed for the 41-70 μm size class, as the river discharge decreases, sediment of the 71-125 μm size class is deposited at Farié-Haoussa, Latakabiey, Niamey and Diabou-Kiria.

- The sediment transport dynamics for the 126-630 μm size class is described in Figure V-38. Sediment of this size is generally deposited at all stations along the middle Niger River in June. The river's sediment transporting capacity in September is enough to transport the 126-630 μm size sediment only at Kandadji and Farié-Haoussa. In December, the 126-630 μm sediment class is transported and sustained in suspension at all stations along the Niger River except at Niamey and Diabou-Kiria. In March as river discharge decreases, sediment of the 126-630 μm class is deposited.

- The coarsest sediment class (631-1600 μm) is only sustained in suspension at Kandadji in September and at Farié-Haoussa and Niamey in December. At all other periods and along the middle Niger River, the Niger rivers suspended sediment transport capacity does not sustain sediment of this size in suspension.

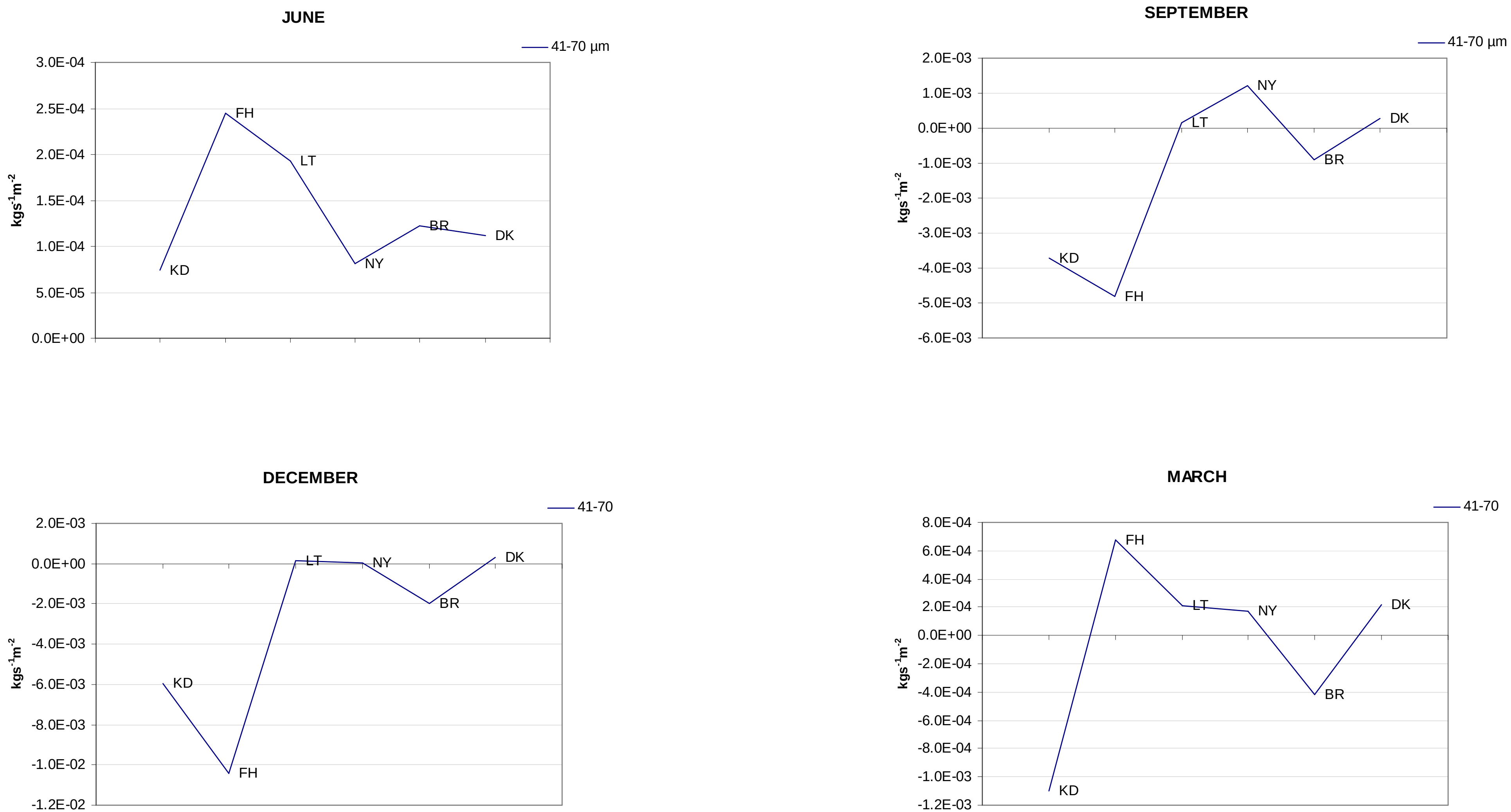


Figure V- 36: Suspended sediment dynamics of the 41-70 µm size class

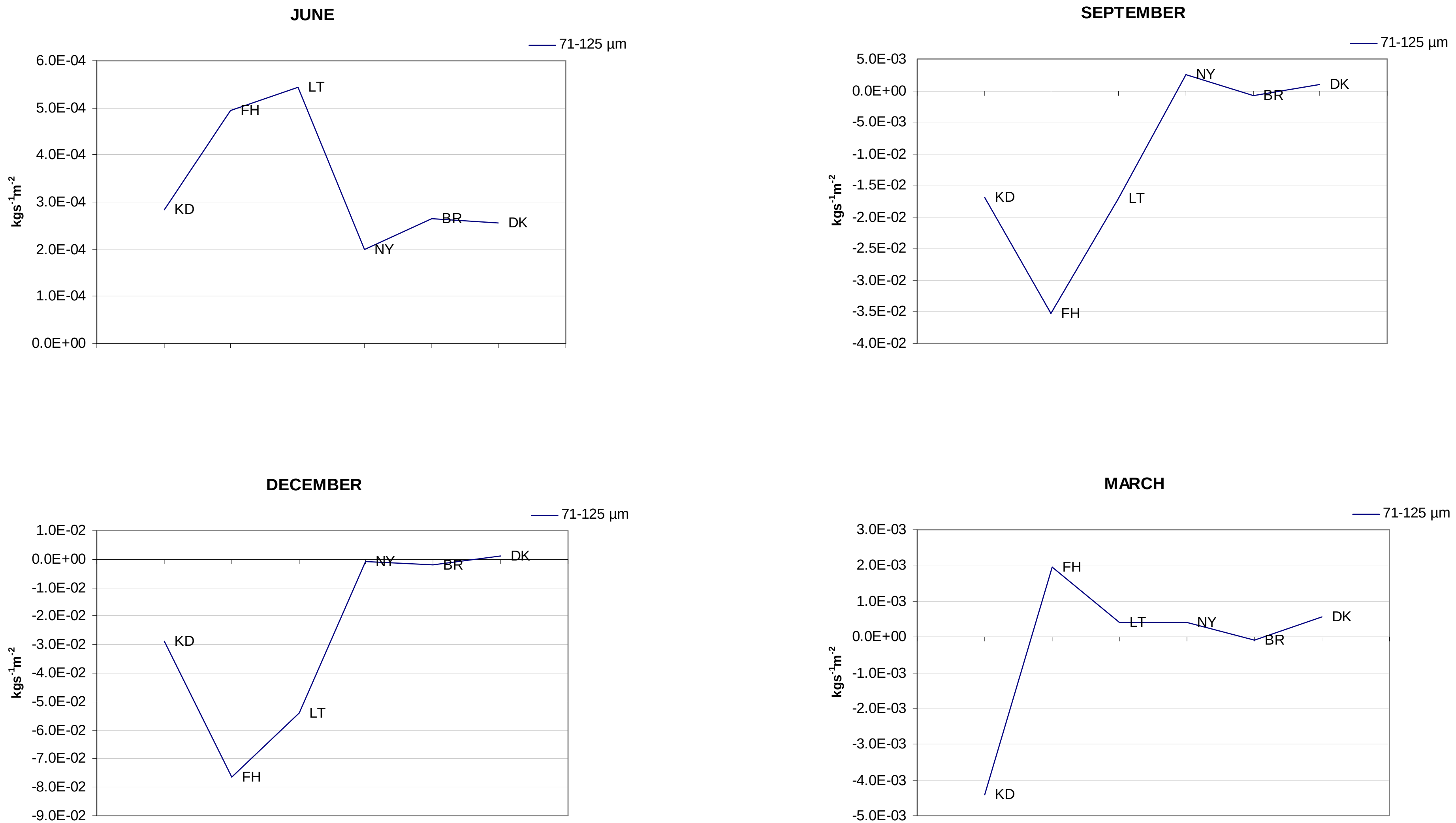


Figure V- 37: Suspended sediment dynamics of the 71-125 µm size class

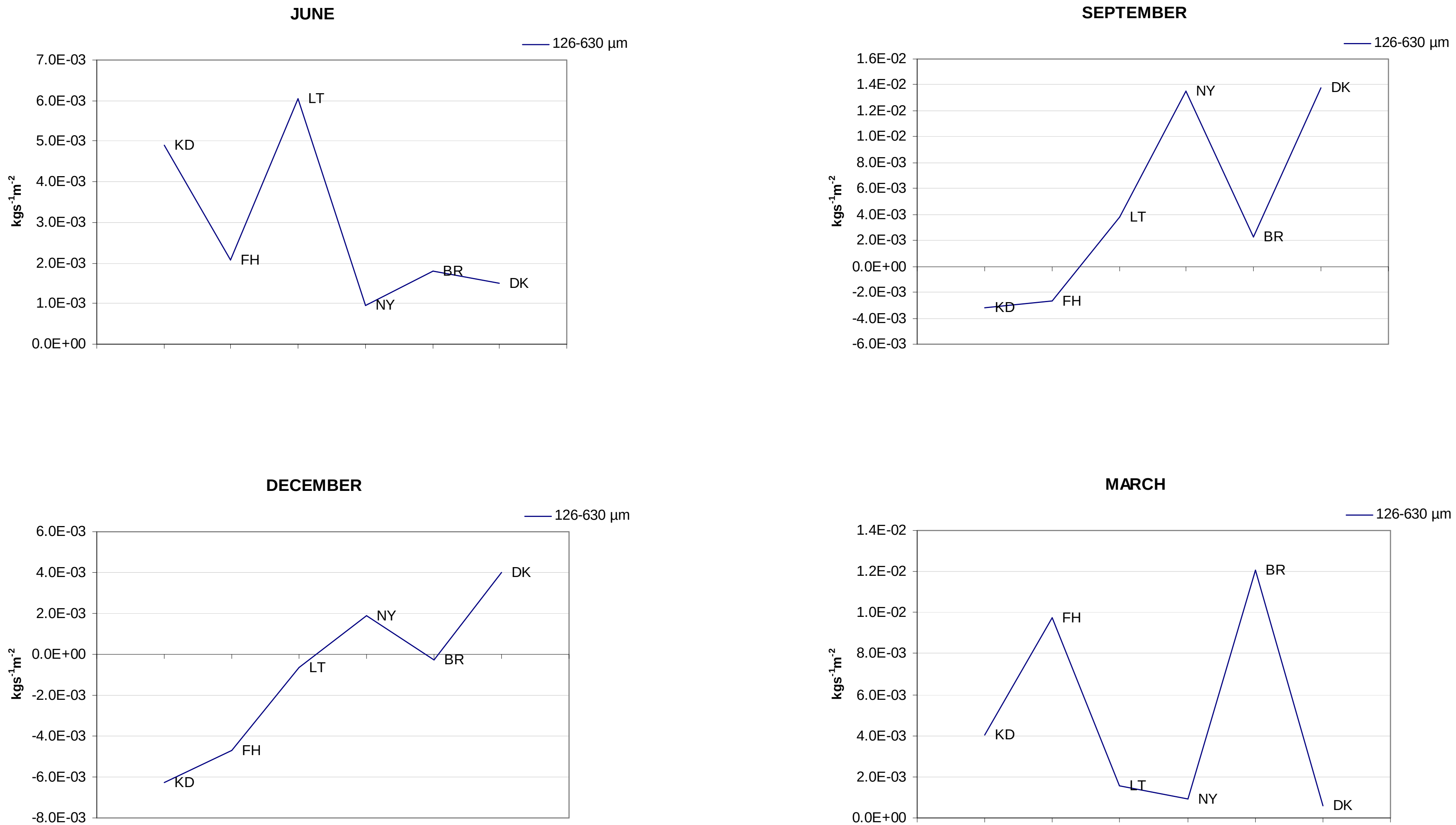


Figure V- 38: Suspended sediment dynamics of the 126-630 µm size class

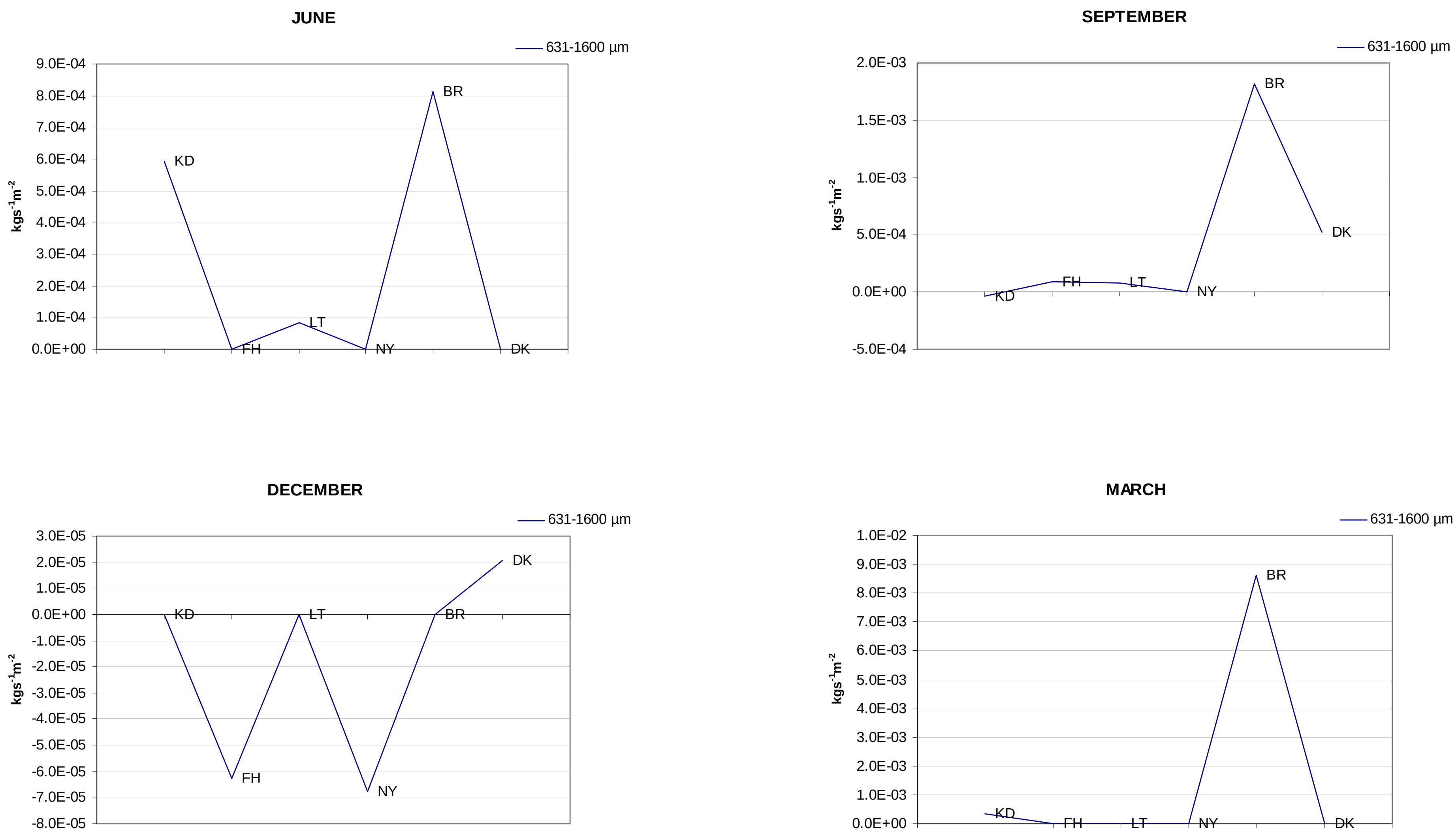


Figure V- 39: Suspended sediment dynamics of the 631-1600 µm size class

The results obtained in this analysis indicate that the most critical depositing sediment size is the 126-630 μm class. The area around Niamey is particularly susceptible to the deposition of sediment of this size.

8. Conclusions

The sediment transport research carried out in this part of the study considered the sediment composition and sampling frequency in order to achieve the aims of the study.

An analysis of the suspended sediment sizes transported by the rivers in the study area during the study period highlighted:

- The complex relationships between sediment size, river discharge and rainfall as well as the impact of seasonal effects on sediment transport.

The sediment supply at different stations along the Niger River were characterised by analysing the seasonal evolution of sediment sizes transported in suspension during the study period.

- The sediment transport at Ayorou was seen to be supply limited, with the percentage of very fine particles (0-40 μm) decreasing with increasing discharge even at the start of the rainy season.
- Very fine sediment (0-40 μm) was transported at Kandadji, Farié-Haoussa, Latakabiey, and Diabou-Kiria in a direct relationship with river discharge at the start of the rainy season. This indicates that due to raindrop impact at the start of the rainy season, very fine sediment is available for transport. The very fine sediment are due to easily detachable top soil that become available after the long dry season and to some extent to aeolian sediment deposits.
- The behaviour of very fine (0-40 μm) and coarse (41-630 μm) particles at Niamey and Brigambou, indicates two distinct sediment sources to these stations during the rising limb of the rainy season hydrograph.

The study identified and quantified tributary sediment sources, sediment fluxes for tributaries and along the Niger River.

- The suspended sediment inputs of the major Sahelian tributaries of the middle Niger River (the Gorouol River and the Sirba River) were quantified. The calculated sediment flux of the Gorouol River was between 480,000 and over 1 million tonnes for the study period. The sediment flux of the Sirba was between 500,000 and 1.3 million tonnes for the study period. The variability in sediment discharge was largely due to the difference in water discharged during a water year by the two rivers. The difference in the sediment supply and transfer behaviours of the two Sahelian basins was highlighted.

- The Sudanian Mékrou River basin appeared to supply less sediment to the middle Niger River during the study period according to the sediment balance between the stations upstream and downstream of its confluence with the Niger River.
- The suspended sediment flux along the middle Niger River was quantified from measured sediment concentration and river discharge values to be between 11 and 16 million tonnes per year, with a maximum flux occurring around Niamey.
- The study showed that other significant sediment sources exist between Latakabiey and Niamey even though there are no major tributaries between these two stations. The ephemeral "koris" were advanced as a possible source for this surplus sediment supporting the results obtained in part II of this work.

The deposition trends of sediment along the middle Niger River, seasonal timescales and the main controlling factors of sediment deposition were highlighted in this study.

- A comparison of measured suspended sediment concentration and calculated sediment transport capacity of the middle Niger River provided an indication to the major sediment deposition areas and the sediment size classes that are most liable to deposition. The area around Niamey was highlighted as an area of sediment deposition, of sand-sized sediment between 126 and 630 μm.

Conclusions and Perspectives

1. General Summary

The overall aim of this study was to gain an understanding of the sediment dynamics of the middle Niger River basin particularly in a period of degrading land cover. The study was carried out via three main axes: land cover analyses, hydrological analyses, sediment measurement and analyses.

In order to achieve the aim of this research, five principal objectives were set.

- The first objective was to describe and quantify the land cover changes that have taken place over the last three to four decades in the Sahelian part of the study area and contrast it with the Sudanian part of the study area. The working hypothesis were that in most of the study area during this period, wooded vegetation was replaced by bare soil surfaces in the form of cultivated land, human settlements, and depleted vegetation bands leading to higher erosion. The land cover change analysis although limited by the availability of images showed that bare soil surfaces in the Sahelian basins increased between the 1970's and 1999, from 60% to 75% for the Gorouol basin and from 45% to 71% for the Sirba basin. However, the study showed that a slight reduction in bare soil surfaces occurred between 1992 and 1999, for the Gorouol and between 1989 and 1999 for the Sirba. The Mékrou basin was affected to a lesser degree by the vegetation removal between 1973 and 2000, the percentage of trees decreased by only 6% between 1973 and 2000. This trend is comparable with land cover observations particularly in the Sahel region.

  In summary, the land cover analysis showed that land cover change in the study area is dynamic, with more rapid change occurring in the Sahelian basins in comparison to the Mékrou basin. This study attempted to incorporate Corona imagery to the study of land cover change in the Sahel; it was shown that while the use of this type of imagery is time- and storage space-intensive, such imagery provide useful information particularly in the absence of reliable data.

- The second objective was to determine the impact of changing land cover on sediment transport in the study area. The ideal approach to this question would have been to carry out a comparison of the sediment transport characteristics for two or more distinct land cover states of the study area. Although the land cover trend in the study area was described in part II of this work, and suspended sediment transport data (1976 to 1982) for parts of the study area was available, the difficulty of a direct comparison of sediment data was shown in part V of this study. Because it was not appropriate to make a direct comparison between previous sediment data and data from the present study in order to quantify sediment production change, information about the consequences of the land cover change had to be inferred from surrogate sources. The trend of increasing bare soil surfaces demonstrated in part III of this study occurred at the same time as the increasing tributary contribution and decreasing river discharge of the Niger River at Niamey observed in part IV of this study. Phenomena such as increasing tributary contribution in combination with increased bare soils can be expected to cause the transfer of more sediment from the basin to the middle Niger River. At the same time, the observed reduction in river discharges of the middle Niger and the dominance of rainy season discharge can be expected to have an effect on the ability of the Niger River to efficiently transport sediment.

- The third objective of this work was to study the changes in channel form of the middle Niger River in response to river discharge perturbations between 1965 and 1999. Changes in channel width were observed to have occurred after a time lag of about 5 years from the occurrence of perturbations in river discharge for the middle Niger River. The major changes in channel form in the middle Niger River were observed in the Sahelian part of the study area. The middle Niger River stretch near the Gorouol River (reach 1), after an initial increase in river channel width has continued to narrow because of decreasing river discharge. On the other hand, the middle Niger River near the Sirba river (reach 2), in addition to similar fluctuations that occurred in the upstream stretch (reach 1) has exhibited a widening trend since 1989. While the slight increase in the annual cumulative discharge along the middle Niger River has not had a widening effect on reach 1 it has caused a widening of the channel in reach 2. This is due to the increasing local rainy season component of the hydrograph for the middle Niger River at Niamey (in reach 2) in comparison to the upstream reach 1. This component of the hydrograph in addition to supplying more river discharge also appears to supply more sediment that may have caused a widening of reach 2 between 1989 and 1999.

- The fourth objective of this study was to quantify the sediment transport of the middle Niger River and some of its tributaries. An appropriate sediment-sampling program was set up to achieve this objective. Measured suspended sediment concentration values were transformed to instantaneous sediment flux values. Annual values of sediment flux were calculated for the stations along the middle Niger River and the seasonal sediment input of two Sahelian rivers was calculated.

- The fifth objective of this study was to identify sediment source and deposition areas and the main controlling factors of these phenomena. The effects of vegetation removal and erosion by overland flow were demonstrated by the growth of alluvial fans. The area of one such alluvial fan near Niamey increased from about 0.16 km^2 in 1975 to about

1.24 km² in 1999. Sediment deposits of this nature are a sediment source to the Niger River during the rainy season. With respect to the sediment deposition dynamics in the study area, the working hypothesis was that deposition rates along the middle Niger River are controlled by fluid forces and sediment particle related resistance forces. The sediment transfer analyses carried out in part V indicated that for all size classes and for all phases of river discharge, the stretch between Latakabiey and after Niamey are the major areas of sediment deposition.

Evaluation of methodology applied to the study

This study applied a variety of methods and approaches in order to achieve the set objectives.

The use of satellite imagery when available, for the monitoring of river channel form and sediment deposition using a GIS platform provided an important tool in the quantification of historic changes within the large study area.

Although satellite imagery can provide information on past and present states of land cover, the most accurate use of this method is possible when images are obtained at the same time as ground truth data. The study showed that CORONA imagery could provide qualitative as well as quantitative information for similar studies.

Simple but frequent suspended sediment sampling combined with occasional cross-sectional sampling appears to be a cost effective and reasonably accurate method for the monitoring of a large river like the Niger.

2. Perspectives for further work

The setting up of a medium-term sediment-sampling program that takes the sediment size composition into consideration as highlighted in this study would provide basin managers with more information on the sediment dynamics of the study area than was possible during the study period.

The importance of river discharge measurements in the middle Niger basin cannot be overstated because they are important for understanding changes in hydrology and sediment transport. The usefulness of tools for simulating river flood propagation was highlighted, as long as the results they produce are properly verified. Such tools need to be updated regularly in order to maintain the accuracy of results obtainable.

The results of this research have shown the existence of significant sediment sources other than the gauged tributaries of the middle Niger River. This is particularly so around Niamey. In order to improve the knowledge of the sediment dynamics in the study area, it appears necessary to study the flow and sediment characteristics of the ephemeral streams known as "koris" that exist in this area. A further study into the representatitivity of suspended sediment concentration across river sections in the study area may improve the reliability of single samples. Relationships such as velocity and flow depth with concentration may be investigated.

This research has shown that the water resources in the study area are strongly influenced by climatic variability, and that river flow regimes and quantities are important factors that control the transport and deposition of sediment. Interaction with research programs like AMMA (African Monsoon Multidisciplinary Analyses), that aim to improve the understanding of the West African Monsoon and its influence on the environment and water resources, could help to predict the possible effects of future climatic variability on sediment transport in the region. Furthermore, the impacts of proposed hydraulic works on the sediment transport of the regions watercourses could be investigated in the framework of such collaborations.

3. Conclusions

The results of the research presented in this document represents an attempt at gaining a better understanding of the impacts of a rapidly changing environment due to climatic and anthropogenic factors on sediment transport in the middle Niger River. The effects of increased bare soil surfaces on sediment transfer to the middle Niger River is demonstrated in terms of increasing tributary contribution, increasing rainy season discharge of the middle Niger River and the increasing area of alluvial deposits. The spatial and temporal discontinuity in sediment flux observed along the middle Niger River between Latakabiey, Niamey and Brigambou, is explained by the results obtained in the sediment deposition analyses of the middle Niger River.

This research work in addition to providing basic insight on the sediment transfer functioning of the middle Niger River, can be helpful to basin managers and engineers in planning for hydraulic works along the river and as a basis for comparison of future sediment studies in the area.

Bibliography

Agnew, C., and A. Warren (1996), A framework for tackling drought and land degradation, Journal of Arid Environments, 33, 309-320.

Agnew, C. T., and A. Chappell (1999), Drought in the Sahel, GeoJournal, 48, 299-311.

Albergel, J. (1987), Sécheresse, désertification et ressources en eau de surface - Application aux petits bassins du Burkina Faso, in The influence of Climate Change and Climate Variability on the Hydrologic Regime and Water Resources, edited by S. I. Solomon, M. Beran and W. Hogg, pp. 355-365, IAHS Publication No 168, Wallingford.

Ali, A., and T. Lebel (2008), The Sahelian standardized rainfall index revisited, International Journal of Climatology, DOI 10.1002/joc.1832.

Alvarez, A. (2005), Channel planform dynamics of an alluvial tropical river, 185 pp, Texas A&M University.

Amani, A., and M. Nguetora (2002), Evidence d'une modification du régime hydrologique du fleuve Niger à Niamey, in Regional Hydrology: Bridging the Gap Between Research and Practice, edited by H. Van Lannen and S. Demuth, pp. 449–456, IAHS.

Andersen, G. L. (2006), How to detect desert trees using corona images: Discovering historical ecological data, Journal of Arid Environments, 65(3), 491-511.

Andersen, I., O. Dione, M. Jarosewich-Holder, and J. C. Olivry (2005), The Niger River Basin. A Vision for Sustainable Management, 144 pp., The World Bank, Washington D.C.

Anyamba, A., and C. J. Tucker (2005), Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981–2003, Journal of Arid Environments, 63, 596-614.

ASTM Standard D 3977-1997 (2007), Standard Test Methods for Determining Sediment Concentration in Water Samples, edited, ASTM International, West Conshohocken, PA DOI 10.1520/D3977-97R07 Section 1-26.

Baban, S. M. J. (1995), The use of Landsat imagery to map fluvial sediment discharge into coastal waters, Marine Geology, 123, 263-270.

Beaudet, G., R. Coque, P. Michel, and P. Rognon (1977), Y a-t-il eu capture du Niger?, Bull. Ass. Géogr. Fr., 445-446, 215-222.

Bellion, Y., J-C. (1987), Histoire géodynamique post paléozoïque de l'Afrique de l'Ouest d'après quelques bassins sédimentaires, 296 pp, Université d'Avignon et des pays de Vaucluse, Avignon.

Bessoles, B. (1977), Géologie de l'Afrique: Le craton ouest africain, 402 pp., BRGM, Paris.

Black, R. (1985a), Le pan-africain et son influence sur l'évolution géologique au phanérozoïque, in Evolution Géologique de l'Afrique, edited by R. Black, pp. 115-141, CIFEG, Paris.

Black, R. (1985b), Introduction générale sur la structure du continent africain, in Evolution Géologique de l'Afrique, edited by R. Black, pp. 7-16, CIFEG, Paris.

Blott, S. J., and K. Pye (2001), Gradistat: A grain size distribution and statistics package for the analysis of unconsolidated sediments, Earth Surface Processes and Landforms, 26, 1237-1248.

Bonfiglio, A., V. Cuomo, M. Lanfredi, and M. Macchiato (2002), Interfacing NOAA/AVHRR NDVI and soil truth maps for monitoring vegetation phenology at a local scale in a heterogenous landscape of Southern Italy, International Journal of Remote Sensing, 23(20), 4181-4195.

Bricquet, J. P. (1993), Les écoulements du Congo à Brazzaville et la spatialisation des apports, in Grands Bassins Fluviaux, edited by J.-C. Olivry and J. Boulègue, pp. 27-38, ORSTOM Editions, Paris.

Brunet-Moret, Y., P. Chaperon, J. P. Lamagat, and M. Molinier (1986), Monographie hydrologique du Fleuve Niger. Tome II- Cuvette Lacustre et Niger Moyen, 506 pp., ORSTOM, Paris.

Burkham, D. E. (1985), An Approach for Appraising the Accuracy of Suspended-sediment DataRep., 18 pp, USGS, Washington 18 pp.

Caby, R. (2003), Terrane assembly and geodynamic evolution of central-western Hoggar: a synthesis, Journal of African Earth Sciences, 37, 133-159.

Cameron, A. D., D. R. Miller, F. Ramsay, I. Nikolaou, and G. C. Clarke (2000), Temporal measurement of the loss of native pinewood in Scotland through the analysis of orthorectified aerial photographs, Journal of Environmental Management, 58, 33-43.

Casenave, A., and C. Valentin (1989), Les états de surface de la zone Sahélienne- Influence sur l'infiltration, 229 pp., ORSTOM, Paris.

Chaperon, P. (1971), Les Etudes d'hydrologie de Surface 1956-1970Rep., 30 pp, ORSTOM, Paris.

Charney, J. G. (1975), Dynamics of deserts and drought in the Sahel, Quarterly Journal of the Royal Meteorological Society, 101, 193-202.

Chinen, T. (1999), Recent accelerated gully erosion and its effects in dry savanna, southwest of Niger., in Human response to drastic change of environments in Africa, edited by N. Hori, pp. 67-102, Tokyo Metropolitan University.

Cooley, M. E., and R. M. Turner (1982), Application of Landsat products in range- and water-management problems in the Sahelian zone of Mali, Upper Volta, and Niger, edited by U. S. D. o. t. Interior, p. 52, United States Government Printing Office, Washington.

Courel, M.-F. (1985), Etude de l'évolution récente des milieux sahéliens à partir des mesures fournies par les satellites, 407 pp, Université de Paris I, Paris.

Cunge, J. A., F. M. Holly, and A. Verwey (1980), Practical aspects of computational river hydraulics, 416 pp., Pitman Publishing Ltd., London.

Davis, T. (2003), Agricultural water use and river basin conservationRep., 40 pp, WWF-World Wide Fund For Nature, Gland.

Desconnets, J. C., J. D. Taupin, T. Lebel, and C. Leduc (1997), Hydrology of the HAPEX-Sahel Central Super-Site: surface water drainage and aquifer recharge through the pool systems, Journal of Hydrology, 188-189, 155-178.

Descroix, L. (2003), Les conséquences hydrologiques de l'évolution des usages des sols, 78 pp, Université Joseph Fourier, Grenoble Mémoire d'Habilitation à Diriger des Recherches (HDR).

Descroix, L., E. Gautier, A. L. Besnier, O. Amogu, D. Viramontes, and J. L. G. Barrios (2005), Sediment budget as evidence of land-use changes in mountainous areas: two stages of evolution, in Sediment Budgets 2, edited by A. J. Horowitz and D. E. Walling, pp. 262-270, IAHS Publication no. 292, Foz do Iguaçu.

Descroix, L., et al. (2009), Spatio-temporal variability of hydrological regimes around the boundaries between Sahelian and Sudianian areas of West Africa: A synthesis, Journal of Hydrology, doi:10.1016/J.jhydrol.2008.1012.1012.

Diallo, D. (2000), Erosion des sols en zone soudanienne du Mali: Transfert des matériaux érodés dans le bassin versant de Djitiko(Haut Niger), 202 pp, Université Joseph Fourier, Grenoble.

Diello, P., G. Mahé, J. E. Paturel, A. Dezetter, F. Delclaux, E. Servat, and F. Ouattara (2005), Relations indices de végétation-pluie au Burkina Faso: cas du bassin versant du Nakambé, Hydrological Sciences Journal, 50(2), 207-221.

Dinehart, R. L., and J. R. Burau (2005), Repeated surveys by acoustic Doppler current profiler for flow and sediment dynamics in a tidal river, Journal of Hydrology, 314, 1-21.

Diouf, A., and E. F. Lambin (2001), Monitoring land-cover changes in semi-arid regions: remote sensing data and field observations in the Ferlo, Senegal., Journal of Arid Environments, 48, 129-148.

Dolman, A. J., J. H. C. Gash, J. P. Goutorbe, Y. Kerr, T. Lebel, S. D. Prince, and J. N. M. Sricker (1997), The role of the land surface in Sahelian Climate: HAPEX-Sahel results and future research needs., Journal of Hydrology, 188-189, 1067-1079.

Doxoran, D., J.-M. Froidefond, S. Lavender, and P. Castaing (2002), Spectral signature of highly turbid waters- Application with SPOT data to quantify suspended particulate matter concentrations, Remote Sensing of Environment, 81, 149-161.

Dracup, J. A., K. S. Lee, and E. G. Paulson (1980), On the definition of droughts, Water Resources Research, 16(2), 297-302.

Dregne, H. E. (1986), Desertification of arid lands, in Physics of desertification, edited by F. El-Baz and M. H. A. Hassan, Martinus, Nijhoff, Dordrecht, The Netherlands http://www.ciesin.org/docs/002-193/002-193.html (1 December 2005).

Driessen, P., J. Deckers, O. Spaargaren, and F. Nachtergaele (Eds.) (2001), Lecture notes on the major soils of the world, 334 pp., FAO, Rome.

El-Raey, M., S. H. Sharaf El-Din, A. A. Khafagy, and A. I. Abo Zed (1999), Remote sensing of beach erosion/accretion patterns along Damietta-Port Said shoreline, Egypt, International Journal of Remote Sensing, 20(6), 1087-1106.

Ennih, N., and J.-P. Liégeois (2008), The boundaries of the West African craton, with special reference to the basement of the Moroccan metacratonic Anti-Atlas belt, in The Boundaries of the West African Craton, edited by N. Ennih and J.-P. Liégeois, pp. 1-17, Geological Society London, London.

FAO (1997), Irrigation potential in Africa: A basin approach, edited, FAO Land and Water Development Division, Rome http://www.fao.org/docrep/W4347E/W4347E00.htm (5 December 2005).

FAO (2003), The digital soil map of the world, edited, Land and Water development division, Rome.

FAO (2008a), FAOSTAT, edited, http://faostat.fao.org/site/567/default.aspx#ancor (5 October 2008).

FAO (2008b), Web LocClim, edited, http://faostat.fao.org/default.aspx (3 September 2008).

Filizola, N. (2003), Transfert sédimentaire actuel par les fleuves amazoniens, 292 pp, Université P. Sabatier, Toulouse.

Foley, G., W. Floor, G. Madon, E. M. Lawali, P. Montagne, and K. Tounao (1997), The Niger Household Energy Project: Promoting rural fuelwood markets and village management of natural woodlands, edited, The World Bank, Washington D.C. 103 pp.

Foster, I. D. L., R. Millington, and R. G. Grew (1992), The impact of particle size controls on stream turbidity measurement; some implications for suspended sediment yield estimation, in Erosion and Sediment Transport Monitoring Programmes in River Basins, edited by J. Bogen, D. E. Walling and T. J. Day, pp. 51-62, IAHS, Oslo,Norway.

Fowler, M. J. F. (2004), Declassified CORONA KH-4B satellite photography of remains from Rome's desert frontier, International Journal of Remote Sensing, 25(18), 3549-3554.

Frihy, O. E., K. M. Dewidar, S. M. Nasr, and M. M. El Raey (1998), Change detection of the northeastern Nile Delta of Egypt: shoreline changes, Spit evolution, margin changes of Manzala lagoon and its islands, International Journal of Remote Sensing, 19(10), 1901-1912.

Fu, B. J., W. W. Zhao, L. D. Chen, Z. F. Liu, and Y. H. Lu (2005), Eco-hydrological effects of landscape pattern change, Landscape and Ecological Engineering, 1, 25-32.

Gallaire, R. (1986), Le Niger à Kandadji: Synthèse des EtudesRep., ORSTOM, Paris 152 pp.

Gallaire, R. (1995), Données sur les transports du Niger moyen entre Kandadji et Niamey, in Grands Bassins Fluviaux Périatlantiques: Congo, Niger, Amazone, edited by J. C. Olivry and J. Boulègue, pp. 317-332, ORSTOM Editions, Paris.

Gallaire, R., and R. Gathelier (1982), Le Niger à Kandadji: Etude Hydrologique 1981Rep., ORSTOM, Niamey 56 pp.

Gallaire, R., P. Harang, and R. Gathelier (1981), Le Niger à Kandadji: Etude Hydrologique 1980Rep., ORSTOM, Niamey 57 pp.

Gallaire, R., H. El Harmouchi, P. Ribstein, Y. Sardouk, and R. Gathelier (1982), Le Niger à Kandadji: Etude Hydrologique 1981 (Campagne 1981-1982)Rep., ORSTOM, Niamey 69 pp.

Galle, S., M. Ehrmann, and C. Peugeot (1999), Water balance in a banded vegetation pattern :A case study of tiger bush in western Niger, Catena, 37, 197-216.

Gilvear, D., S. Winterbottom, and H. Sichingabula (2000), Character of channel planform change and meander development: Luangwa River, Zambia, Earth Surface Processes and Landforms, 25, 421-436.

Gomez, B., L. A. K. Mertes, J. D. Phillips, F. J. Magilligan, and L. A. James (1995), Sediment characteristics of an extreme flood: 1993 upper Mississippi River valley, Geology, 23(11), 963-966.

Goosens, R., A. De Wulf, J. Bourgeois, W. Gheyle, and T. Willems (2006), Satellite imagery and archaeology: the example of CORONA in the Altai Mountains, Journal of Archaeological Science, 33, 745-755.

Goudie, A. S. (2005), The drainage of Africa since the Cretaceous, Geomorphology, 67, 437-456.

Grosse, G., L. Schirrmeister, V. V. Kunitsky, and H. W. Hubberten (2005), The use of CORONA images in remote sensing of periglacial geomorphology: An illustration from the NE Siberian coast, Permafrost and Periglacial Processes, 16, 163-172.

Grove, A. T. (1972), The load carried by some West African rivers, Journal of Hydrology, 16, 277-300.

Grove, A. T. (1978), Geographical Introduction to the Sahel, The Geographical Journal, 144(3), 407-415.

Gupta, A., and H. Fox (1974), Effects of high-magnitude floods on channel form: A case study in Maryland piedmont, Water Resources Research, 10(3), 499-509.

Hagerty, D. J. (1991a), Piping/sapping erosion. I: Basic considerations, Journal of Hydraulic Engineering, 117(8), 991-1008.

Hagerty, D. J. (1991b), Piping/sapping erosion. II: Identification-Diagnosis, Journal of Hydraulic Engineering, 117(8), 1009-1025.

Harang, P., and R. Gathelier (1979), Le Niger à Kandadji: Etude Hydrologique 1978 et 1979Rep., ORSTOM, Niamey 17 pp.

Hein, L., and N. DeRidder (2006), Desertification in the Sahel: a reinterpretation, Global Change Biology, 12, 751-758.

Hicks, D. M., and B. Gomez (2003), Sediment Transport, in Tools in Fluvial Geomorphology, edited by G. M. Kondolf and H. Piégay, pp. 426-461, John Wiley & Sons Ltd., Chichester.

Hoepffner, M. (1978), Le Niger à Kandadji- Etude Hydrologique 1976 - 1977Rep., ORSTOM, Niamey 64 pp.

Holly, F. M., and J. B. Parrish (1993), Description and evaluation of Program: CARIMA, Journal of Irrigation and drainage Engineering, 119(4), 703-713.

Hooke, J. (2003), Coarse sediment connectivity in river channel systems: a conceptual framework and methodology, Geomorphology, 56, 79-94.

Hountondji, Y., P. Ozer, and J. Nicolas (2004), Mise en évidence des zones touchées par la désertification par télédétection à basse résolution au Niger, Cybergeo: Revu européenne de géographie, 291, 1-18.

Huang, H. Q., and G. C. Nanson (2007), Why some alluvial rivers develop an anabranching pattern, Water Resources Research, 43 W07441 DOI 10.1029/2006WR005223.

Hulme, M. (2001), Climatic perspectives on Sahelian desiccation: 1973-1998, Global Environmental Change, 11, 19-29.

Hulme, M., R. Doherty, T. Ngara, M. New, and D. Lister (2001), African climate change: 1900–2100, Climate Research, 17, 145-168.

IGN (1979), Etude du fleuve Niger: Réalisation cartographique préliminaire à l'établissement du MODELE MATHEMATIQUE DU FLEUVE NIGER, PLANCHE 1-15, Institut Géographique National, Paris.

Jacobberger, P. A. (1988), Drought-related changes to geomorphologic processes in central Mali, Geological Society of America Bulletin, 100, 351-361.

Khan, N. I., and A. Islam (2003), Quantification of erosion patterns in the Brahmaputra-Jamuna River using geographical information system and remote sensing techniques, Hydrological Processes, 17, 959-966.

Kondolf, G. M., T. E. Lisle, and G. M. Wolman (2003), Bed Sediment Measurement, in Tools in Fluvial Geomorphology, edited by G. M. Kondolf and H. Piégay, pp. 347-395, John Wiley & Sons Ltd., Chichester.

Kuper, M., J.-C. Olivry, and A. Hassane (2002), Le fleuve Niger: Une ressource à partager, in L'Office du Niger, grenier à riz du Mali, edited by P. Bonneval, M. Kuper and J.-P. Tonneau, pp. 75-96, Cirad-Karthala, Montpellier.

L'Hôte, Y., P. Dubreuil, and J. Lerique (1996), Carte des types de climats " en Afrique Noire à l'ouest du Congo". Rappels, et extensions aux régimes hydrologiques., in L'hydrologie tropicale: géoscience et outil pour le développement, edited by P. Chevallier and B. Pouyaud, pp. 55-65, IAHS Publication no. 238.

L'Hôte, Y., G. Mahé, and B. Somé (2003), The 1990s rainfall in the Sahel: the third driest decade since the beginning of the century, Hydrological Sciences Journal,, 48(3), 493-496.

L'Hôte, Y., G. Mahé, B. Somé, and J. P. Triboulet (2002), Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues, Hydrological Sciences-Journal, 47(4), 563-572.

Lane, A. (2004), Bathymetric evolution of the Mersey Estuary, UK, 1906-1997: causes and effects, Estuarine, Coastal and Shelf Science, 59, 249-263.

Laraque, A., G. Mahé, D. Orange, and B. Marieu (2001), Spatio-temporal variations in hydrological regimes within Central Africa during the XXth Century, Journal of Hydrology, 245(1-4), 104-117.

Lauer, D. T., S. A. Morain, and V. V. Salomonson (1997), The Landsat Program: Its Origins, Evolution, and Impacts, Photogrammetric Engeering & Remote Sensing, 63(7), 831-838.

Le Houerou, H. N. (1980), The rangelands of the Sahel, Journal of Range Management, 33, 41-46.

Leblanc, M. J., G. Favreau, S. Massuel, S. O. Tweed, M. Loireau, and B. Cappelaere (2008), Land clearance and hydrological change in the Sahel: SW Niger, Global and Planetary Change, 61, 135-150.

Lienou, G. (2007), Impacts de la variabilité climatique sur les ressources en eau et les transports de matières en suspension de quelques bassins versants représentatifs au Cameroun, 405 pp, Université de Yaounde 1, Yaounde.

Liu, J., M. Linderman, Z. Ouyang, L. An, J. Yang, and H. Zhang (2001), Ecological degradation in protected areas: The case of Wolong Nature reserve for Giant Pandas, Science, 292, 98-101.

Loireau, M. (1998), Espaces-Ressources-Usages: Spatialisation des interactions dynamiques entre les systèmes sociaux et les systèmes écologiques au Sahel nigérien, 414 pp, Université Montpellier III- Paul Valery, Montpellier.

Lorenz, H. (2004), Integration of Corona and Landsat Thematic Mapper data for bedrock geological studies in the high Arctic, International Journal of Remote Sensing, 25(22), 5143-5162.

Lu, D., P. Mausel, E. Brondizio, and E. Moran (2004), Change detection techniques, International Journal of Remote Sensing, 25(12), 2365-2407.

Lubès-Niel, H., L. Séguis, and R. Sabatier (2001), Etude de stationnarité des caractéristiques des événements pluvieux de la station de Niamey sur la période 1956 - 1998, Sciences de la Terre et des planètes, 333, 645-650.

Ludwig, W., and J.-L. Probst (1998), River sediment discharge to the Oceans: Present-day controls and global budgets, American Journal of Science, 298(4), 265-295.

Mahé, G., J. C. Olivry, and E. Servat (2005a), Sensibilité des cours d'eau ouest-africains aux changements climatiques et environnementaux: extrêmes et paradoxes, in Regional Hydrological Impacts of Climatic Change—Hydroclimatic Variability, edited by S. Frank, T. Wagener, E. Bøgh, H. V. Gupta, L. Bastidas, C. Nobre and C. de Oliveira Galvão, pp. 169-177, IAHS Publ. no 296.

Mahé, G., J. E. Paturel, E. Servat, D. Conway, and A. Dezetter (2005b), The impact of land use change on soil water holding capacity and river flow modelling in the Nakambe River, Burkina-Faso, Journal of Hydrology, 300, 33-43.

Mahé, G., C. Leduc, A. Amani, J. E. Paturel, S. Girard, E. Servat, and A. Dezetter (2003), Augmentation récente du ruissellement de surface en région soudano-sahélienne et impact sur les ressources en eau, in Hydrology of the Mediterranean and semi-arid regions, edited by E. Servat, W. Najem, C. Leduc and S. Ahmed, pp. 215-222, IAHS Publication no 278.

Mahé, G., F. Bamba, D. Orange, L. Fofana, M. Kuper, B. Marieu, A. Soumagel, and N. Cissé (2002), Dynamique hydrologique du delta intérieur du Niger (Mali), in Gestion intégrée des ressources naturelles en zones inondables tropicales, edited by D. Orange, R. Arfi, M. Kuper, P. Morand, Y. Poncet and B. Témé, pp. 179-195, IRD/CNRST.

Mariko, A., G. Mahé, D. Orange, A. Royer, A. Nonguierma, A. Amani, and E. Servat (2002), Suivi des zones d'inondation du delta intérieur du Niger: perspectives avec les données de basse résolution NOAA/AVHRR, in Gestion intégrée des ressources naturelles en zones inondables tropicales, edited by D. Orange, R. Arfi, M. Kuper, P. Morand, Y. Poncet and B. Témé, pp. 231-244, IRD/CNRST.

Mas, J. F. (1999), Monitoring land-cover changes: a comparison of change detection techniques, International Journal of Remote Sensing, 20(1), 139-152.

Mertes, L. A. K., T. Dunne, and L. A. Martinelli (1996), Channel-floodplain geomorphology along the Solimões-Amazon River, Brazil, Geological Society of America Bulletin, 108(9), 1089-1107.

Mohamed, Y. A., B. J. J. M. van den Hurk, H. H. G. Savenije, and W. G. M. Bastiaanssen (2005), Hydroclimatology of the Nile: results from a regional climate model, Hydrology and Earth System Sciences Discussions, 2, 319-364.

Montgomery, D. R., and J. M. Buffington (1997), Channel-reach morphology in mountain drainage basins, GSA Bulletin, 109(5), 596-611.

Moreau, C., D. Demaiffe, Y. Bellion, and A.-M. Boullier (1994), A tectonic model for the locationof Palaeozoic ring complexes in Aïr(Niger, West Africa), Tectonophysics, 234, 129-146.

Nachtergaele, J., and J. Poesen (1999), Assessment of soil losses by ephemeral gully erosion using high-altitude(stereo) aerial photographs, Earth Surface Processes and Landforms, 24, 693-706.

Nathan, R. J., and T. A. McMahon (1990), Evaluation of automated techniques for base flow and recession analyses, Water Resources Research, 26(7), 1465-1473.

National Reconnaissance Office NRO Corona Fact Sheet, edited, National Reconnaissance Office, http://www.nro.gov/corona/facts.html (19 June 2008).

NEDECO (1959), River Studies and recommendations on improvement of Niger and BenueRep., Netherlands Engineering Consultants The Hague., Amsterdam 1000 pp.

Nellis, M. D., J. A. Harrington, and J. Wu (1998), Remote sensing of temporal and spatial variations in pool size, suspended sediment, turbidity, and Secchi depth in Tuttle Creek Reservoir:1993, Geomorphology, 21, 281-293.

Nicholson, S. (2005), On the question of the “recovery” of the rains in the West African Sahel, Journal of Arid Environments, 63, 615-641.

Nicholson, S. E. (1995), Sahel,West Africa, in Encyclopedia of Environmental Biology, edited, pp. 261-275, Academic Press,Inc.

Nicholson, S. E., M. L. Davenport, and A. R. Malo (1990), A comparison of the vegetation response to rainfall in the Sahel and East Africa, using Normalized Difference Vegetation Index from NOAA AVHRR, Climatic Change, 17, 209-241.

Olivry, J.-C., J.-P. Bricquet, and G. Mahé (1993), Vers un appauvrissement durable des ressources en eau de l'Afrique humide?, in Hydrology of Warm Humid Regions (Proceedings of the Yokohama Symposium), edited by J. S. Gladwell, pp. 67-78, IAHS Publication no. 216.

Olivry, J. C., J. P. Bricquet, J. P. Thiebaux, and N. Sigha (1988), Transport de matière sur les grands fleuves des régions intertropicales: les premier résultats des mesures de flux particulaires sur le bassin du fleuve Congo, in Sediment Budgets, edited by M. P. Bordas and D. E. Walling, pp. 509-521, IAHS Publicatiion no. 174, Porto Alegre.

ORSTOM (1970), Monographie Hydrologique du bassin du Niger-3éme partie Le Niger Moyen, 160 pp., ORSTOM Secrétariat d’état aux affaires étrangères, comité interafricain d’études hydrauliques, Paris.

Ozer, P., M. Erpicum, G. Demarée, and M. Vandiepenbeeck (2003), The Sahelian drought may have ended during the 1990s, Hydrological Sciences Journal, 48(3), 489-492.

Park, M. (1815), The Journal of a Mission to the Interior of Africa, in the Year 1805, 373 pp., London.

Paturel, J. E., E. Servat, H. Lubès-Niel, and M. O. Delattre (1997), Variabilité climatique et analyse de séries pluviométriques de longue durée en Afrique de l'Ouest et centrale non sahélienne, Sciences de la Terre et des planètes, 325, 779-782.

Phillips, J. M., B. W. Webb, D. E. Walling, and G. I. L. Leeks (1999), Estimating the suspended sediment loads of rivers in the LOIS study area using infrequent samples, Hydrological Processes, 13, 1035-1050.

Picouet, C. (1999), Géodynamique d’un hydrosysteme tropical peu anthropisé : Le bassin supérieur du Niger et son delta intérieur, 386 pp, Université de Montpellier II, Montpellier.

Pizzuto, J. E. (1995), Downstream fining in a network of gravel-bedded rivers, Water Resources Research, 31(3), 753-759.

Porada, H. (1989), Pan-African rifting and orogenesis in southern equatorial Africa and eastern Brazil, Precambrian Research, 44(2), 103-136.

Quensière, J., J.-C. Olivry, Y. Poncet, and J. Wuillot (1994), Environnement deltaïque, in La pêche dans le delta central du Niger, edited by J. Quensière, pp. 29-80, ORSTOM/Karthala/IER, Paris.

Rasmussen, K., and B. Fog, .Madsen,J.E. (2001), Desertification in reverse? Observations from northern Burkina Faso, Global Environmental Change, 11, 271-282.

Richard, G. A., P. Y. Julien, and D. C. Baird (2005), Statistical analysis of lateral migration of the Rio Grande, New Mexico, Geomorphology, 71, 139-155.

Rigina, O. (2003), Detection of boreal forest decline with high-resolution panchromatic satellite imagery, International Journal of Remote Sensing, 24(9), 1895-1912.

Rodier, J. (1964), Régimes hydrologiques de l'Afrique noire à l'ouest du Congo, 137 pp., ORSTOM, Paris.

Rodier, J., and M. Roche (1978), River Flow in Arid Regions, in Hydrometry: principles and practices, edited, pp. 453-472, J.Wiley, Chichester.

Rodier, J. A., and M. Roche (1984), World catalogue of maximum observed floods, 354 pp., IAHS Publication no. 143.

Rogan, J., J. Franklin, and D. A. Roberts (2002), A comparison of methods for monitoring multi temporal vegetation change using Thematic Mapper imagery, Remote Sensing of Environment, 80, 143-156.

Roose, E. (1996), Land Husbandry- Components and Strategy, 397 pp., Food and Agriculture Organization of the United Nations, Rome.

Rooseboom, A., and G. W. Annandale (1981), Techniques applied in determining sediment loads in South African rivers, in Erosion and Sediment Transport Measurement, edited by D. Walling and P. Tacconni, pp. 219-224, IAHS Publication no. 133.

Ruelland, D., A. Dezetter, C. Puech, and S. Ardoin-Bardin (2008), Long-term monitoring of land cover changes based on Landsat imagery to improve hydrological modelling in West Africa, International Journal of Remote Sensing, 29(12), 3533-3551.

Schlüter, T. (2006), Geological Atlas of Africa, edited, Springer Berlin Heidelberg, Berlin 272 pp.

Schumm, S. A. (1977), The fluvial system, 338 pp., John Wiley and Sons Inc.

Seguis, L., B. Cappelaere, G. Milési, C. Peugeot, S. Massuel, and G. Favreau (2004), Simulated impacts of climate change and land-clearing on runoff from a small Sahelian catchment, Hydrological Processes, 18, 3401-3413.

Shaw, E. M. (1994), Hydrology in Practice, Third Edition ed., 569 pp., Routledge, Abingdon, Oxon.

Smith, L. C. (1997), Satellite remote sensing of river inundation area, stage, and discharge: A review, Hydrological Processes, 11, 1427-1439.

Song, C., C. E. Woodcock, K. C. Seto, M. P. Lenney, and S. A. Macomber (2001), Classification and change detection using Landsat TM data: When and how to correct atmospheric effects?, Remote Sensing of Environment, 75, 230-244.

Syvitski, J. P. M., C. J. Vörösmarty, A. J. Kettner, and P. Green (2005), Impact of humans on the flux of terrestial sediment to the global coastal ocean, Science, 308, 376-380.

Tappan, G. G., A. Hadj, E. C. Wood, and R. W. Lietzow (2000), Use of Argon, Corona, and Landsat imagery to assess 30 year of land resource changes in West-Central Senegal, Photogrammetric Engeering & Remote Sensing, 66(6), 727-735.

Tarhule, A. (2005), Damaging rainfall and flooding: The other Sahel hazards, Climatic Change, 72, 355-377.

The ASCE Task Committee on Hydraulics Bank Mechanics and Modeling of River Width Adjustment (1998), River Width Adjustment. I: Processes and Mechanisms, Journal of Hydraulic Engineering, 124(9), 881-902.

Thorne, P. D., P. J. Hardcastle, and R. L. Soulsby (1993), Analysis of Acoustic Measurements of Suspended Sediments, Journal of Geophysical Research, 98(C1), 899-910.

Tucker, C. J., H. E. Dregne, and W. W. Newcomb (1991), Expansion and Contraction of the Sahara Desert from 1980 to 1990, Science, 253(5017), 299-301.

UNEP (2002), Atlas of International Freshwater Agreements, edited by A. T. Wolf, United Nations Environment Programme (UNEP), http://www.transboundarywaters.orst.edu/publications/atlas/ (5 June 2007).

United Nations (2007), World Population prospects: The 2006 Revision, Highlights, Working Paper No. ESAP/P/WP202Rep., Department of Economic and Social Affairs, Population Division, New York 96 pp.

United Nations Population Division (2006), World Population prospects: The 2006 Revision, edited, Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, http://esa.un.org/unpp/ (6 October 2008).

USGS (1996), Declassified Satellite Imagery-1, edited, http://edc.usgs.gov/guides/disp1.html (19 June 2008).

USGS (2005), Landsat: A Global Land-Observation Project - Fact Sheet 2005-3130, edited by U.S Geological Survey, p. 4, U.S Geological Survey,.

USGS (2006), Band Designations, edited, http://eros.usgs.gov/products/satellite/band.html (19 June 2008).

USGS, and NOAA (1984), Landsat 4 Data Users Handbook, edited by U.S.G.S and N.O.A.A, p. 200, U.S Geological Survey, National Oceanic and Atmospheric Administration, Alexandria, VA.

Van Rijn, L. C. (1993), Principles of sediment transport in rivers, estuaries and coastal seas, 650 pp., Aqua Publications, Amsterdam.

Vanacker, V., A. Molina, G. Govers, J. Poesen, G. Dercon, and S. Deckers (2005), River channel response to short-term human-induced change in landscape connectivity in Andean ecosystems, Geomorphology, 72, 340-353.

Visser, S. M., G. Sterk, and D. Karssenberg (2005), Modelling water erosion in the Sahel: application of a physically based soil erosion model in a gentle sloping environment, Earth Surface Processes and Landforms, 30, 1547-1566.

Walling, D. E. (1999), Linking land use, erosion and sediment yields in river basins, Hydrobiologia, 410(1), 223-240.

Weaver, A. V. (1991), The distribution of soil erosion as a function of slope aspect and parent material in Ciskei, Southern Africa, GeoJournal, 23(1), 29-34.

Wende, R., and G. C. Nanson (1998), Anabranching rivers: ridge-form alluvial channels in tropical northern Australia, Geomorphology, 22, 205-224.

White, F. (1983), The Vegetation of Africa; a descriptive memoir to accompany the Unesco/AETFAT/UNSO vegetation map of Africa;Unesco/AETFAT/UNSO vegetation map of Africa; Unesco/AETFAT/UNSO carte de l'Afrique, in Natural resources research, edited, p. 356.

White, K., and H. M. El Asmar (1999), Monitoring changing position of coastlines using Thematic Mapper imagery, an example from the Nile Delta, Geomorphology, 29, 93-105.

Wilkinson, B. H., and B. J. McElroy (2007), The impact of humans on continental erosion and sedimentation, Geological Society of America Bulletin, 119(1/2), 140-156.

Winterbottom, S. J., and D. J. Gilvear (1997), Quantification of channel bed morphology in gravel-bed rivers using airborne multispectral imagery and aerial photography, Regulated Rivers: Research and Management, 13, 489-499.

Wolman, M. G. (1954), A method of sampling coarse river-bed material, Transactions American Geophysical Union, 35, 951-956.

Wren, D. G., B. D. Barkdoll, R. A. Kuhnle, and R. W. Derrow (2000), Field techniques for suspended-sediment measurement, Journal of Hydraulic Engineering, 126(2), 97-104.

Wright, A., W. A. Marcus, and R. Aspinall (2000), Evaluation of multispectral, fine scale digital imagery as a tool for mapping stream morphology, Geomorphology, 33, 107-120.

Yero, K. (2008), L'évolution de l'occupation des sols à l'échelle des bassins versants de Wankama et Tondi Kiboro: Quelles conséquences sur les débits et l'évapotranspiration réelle, 74 pp, Université Abdou Moumouni Niamey, Niamey.

Zhou, W., S. Wang, Y. Zhou, and A. Troy (2006), Mapping the concentrations of total suspended matter in Lake Taihu, China, using Landsat-5 TM data, International Journal of Remote Sensing, 27(6), 1177-1191.

APPENDICES

APPENDIX A

Table A- 1: Estimated and projected agricultural population long term series (decennial) for Bénin, Burkina-Faso, Mali and Niger (1950-2010) from the FAOSTAT database

Year	Agricultural Population(thousand)	Total population (thousand)	% Agricultural population
BENIN			
1950	1776	2005	88.6
1960	1972	2316	85.1
1970	2292	2828	81.0
1980	2498	3709	67.3
1990	3289	5178	63.5
2000	3886	7197	54.0
2010	4329	9793	44.2
BURKINA FASO			
1950	3547	3860	91.9
1960	4093	4455	91.9
1970	4902	5329	92.0
1980	6070	6587	92.2
1990	7882	8532	92.4
2000	10412	11292	92.2
2010	14093	15315	92.0
MALI			
1950	3274	3450	94.9
1960	4048	4317	93.8
1970	5031	5431	92.6
1980	6204	6975	88.9
1990	7628	8893	85.8
2000	9433	11647	81.0
2010	11676	15617	74.8
NIGER			
1950	2498	2613	95.6
1960	3247	3446	94.2
1970	4254	4586	92.8
1980	5662	6206	91.2
1990	7601	8472	89.7

2000	10326	11783	87.6
2010	14010	16430	85.3

Table A- 2: Millet cultivation data for Niger (1961-2007) from the FAOSTAT database

Year	Area Harvested (Hectares)	Yield (Hectogram/hectare)	Year	Area Harvested (Hectares)	Yield (Hectogram/hectare)
1961	1640100	4731	1985	3168705	4577
1962	1840000	5076	1986	3239487	4270
1963	1887000	5145	1987	3016720	3304
1964	1777000	5702	1988	3518003	5020
1965	1810000	4361	1989	3565738	3737
1966	1743000	4829	1990	4606093	3833
1967	1865200	5361	1991	4389733	4175
1968	1895200	3865	1992	4988796	3583
1969	2271900	4821	1993	4675272	3547
1970	2309800	3770	1994	4920056	4000
1971	2355800	4070	1995	5229430*	3383[a]
1972	2194500	4186	1996	5021190*	3507[a]
1973	2007700	3122	1997	4503635	3001
1974	2230000	3957	1998	5366055	4456
1975	1692900	3433	1999	5351201	4291
1976	2526900	4033	2000	5151395	3259
1977	2728500	4142	2001	5231937	4614
1978	2726700	4117	2002	5576500	4490
1979	2922085	4295	2003	5771300	4756
1980	3072360	4438	2004	5604400	3635
1981	3038000	4324	2005	5893900	4500[a]
1982	3083800	4191	2006	6229948	4829[a]
1983	3135550	4181	2007	6170179	4508[a]
1984	3025695	2548			

* *Unofficial figure;* [a] *FAO estimate*

Table A- 3: Estimated agricultural area for Bénin, Burkina-Faso, Mali and Niger (1950-2005) from the FAOSTAT database

Year	Benin	B.Faso	Mali	Niger
1961	1442	8139	31668	31500
1962	1462	8149	31673	31500
1963	1482	8159	31678	31500
1964	1502	8169	31683	31500
1965	1522	8179	31688	31500
1966	1552	8190	31693	31500
1967	1592	8200	31700	31500
1968	1622	8210	31700	32177
1969	1707	8222	31700	32176
1970	1727	8236	31750	31200
1971	1777	8220	31750	31230
1972	1807	8302	31750	31177
1973	1827	8373	31750	30814
1974	1857	8453	31800	29780
1975	1897	8536	31850	29780
1976	1927	8585	32050	29780
1977	1957	8635	32050	29780
1978	1977	8685	32050	29780
1979	1997	8735	32050	29958
1980	2027	8785	32050	30720
1981	2057	8835	32053	30280
1982	2090	8885	32053	30360
1983	2100	8935	32053	31010
1984	2110	8985	32053	30780
1985	2130	9035	32073	30780
1986	2190	9085	32076	31280
1987	2200	9140	32076	31012
1988	2210	9564	32093	31300
1989	2220	9600	32093	31405
1990	2270	9575	32093	33047
1991	2280	9550	32103	34105
1992	2295	9525	32203	35500
1993	2320	9500	33100	35500
1994	2400	9431	35200	35500
1995	2520	9450	35419	36500
1996	2710	9550	36650	36500
1997	2890	9800	37650	36500
1998	3050	9950	37650	36500
1999	3110	10000	37650	37500
2000	3195	10100	38674	37500
2001	3265	10600	39339	38500
2002	3365	10700	39379	38500
2003	3467	10900	39479	38500
2004	3567	10900	39479	38500
2005	3567	10900	39479	38500

Agricultural area refers to:

(a) arable land ,- (b) permanent crops and (c) permanent pastures

Data are expressed in 1 000 hectares. Sources FAO Annual Production Questionnaire - National Statistical Yearbook - Official/Governmental websites Data in (1000 ha)

APPENDIX B

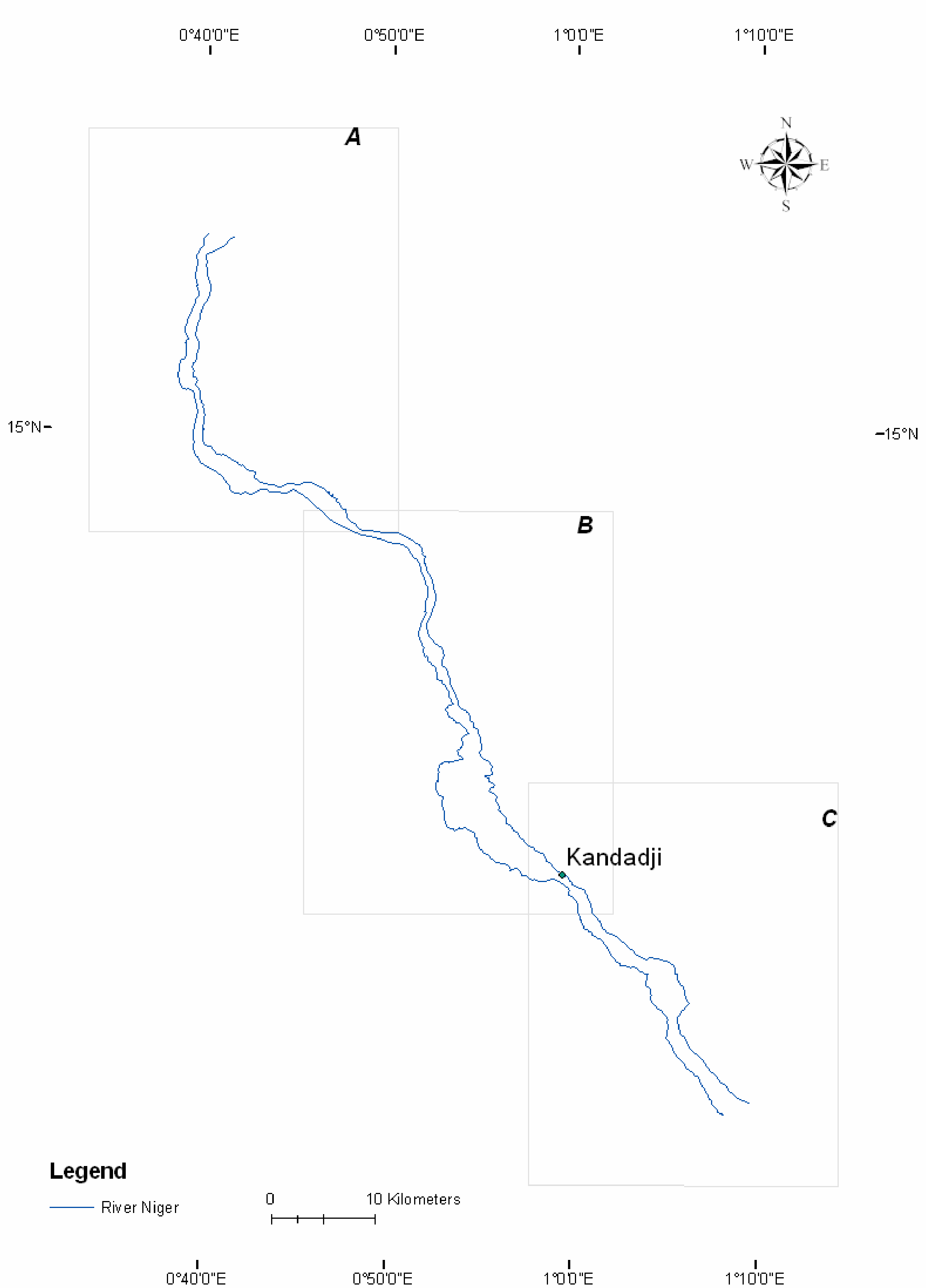


Figure B- 1: Reach 1

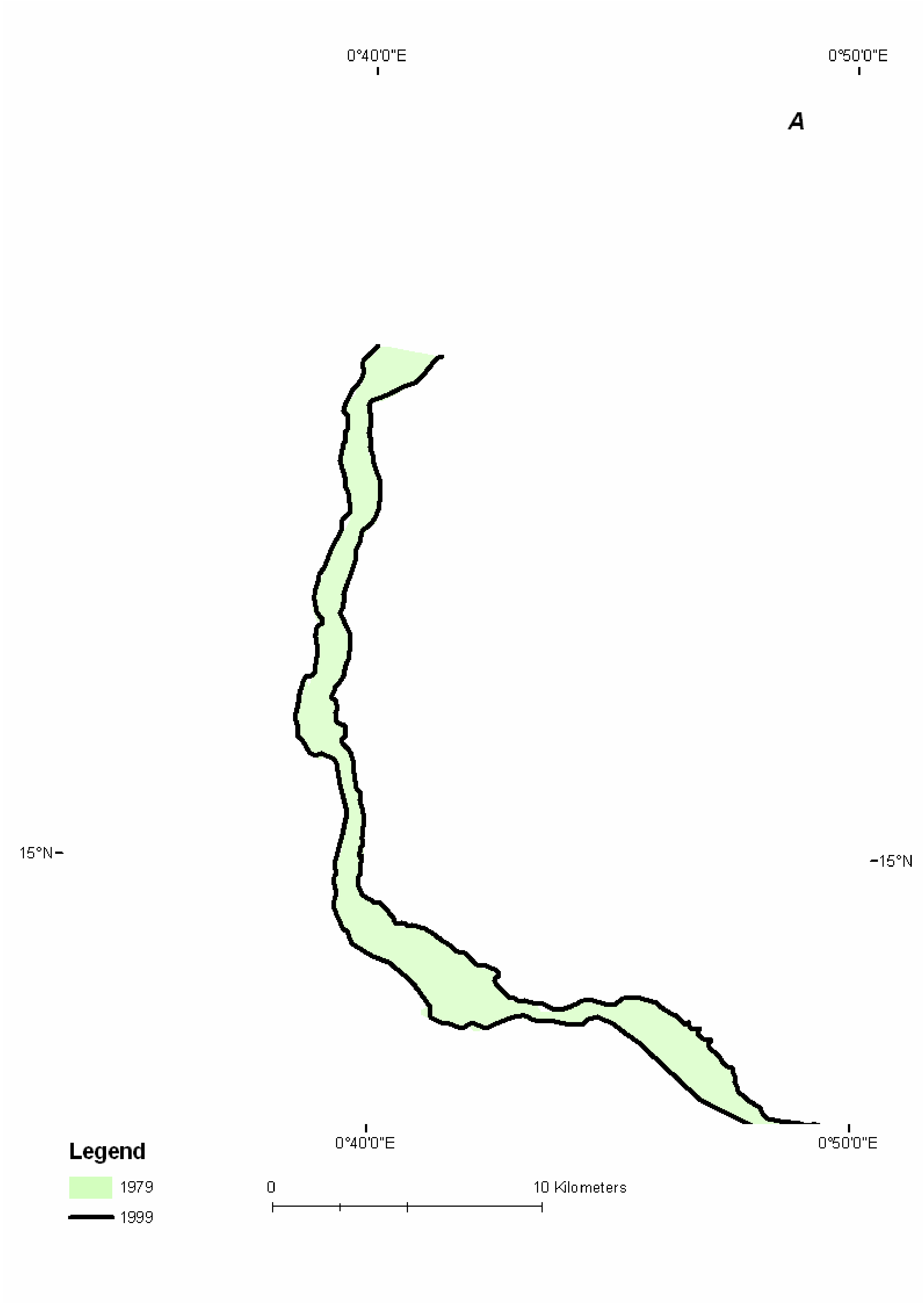


Figure B- 2A: Channel change in Reach 1 (1979-1999)

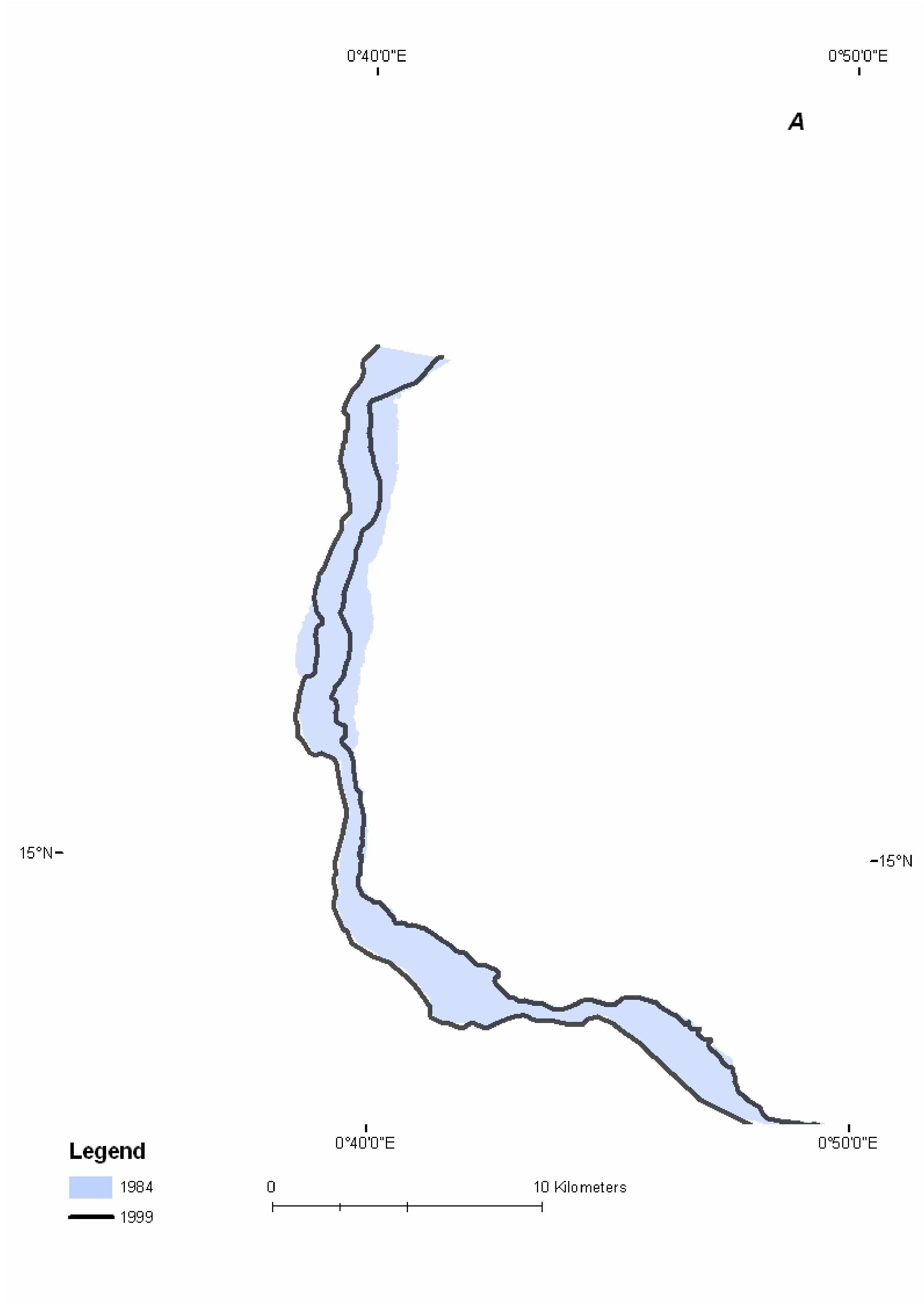


Figure B- 3A: Channel change in Reach 1 (1984-1999)

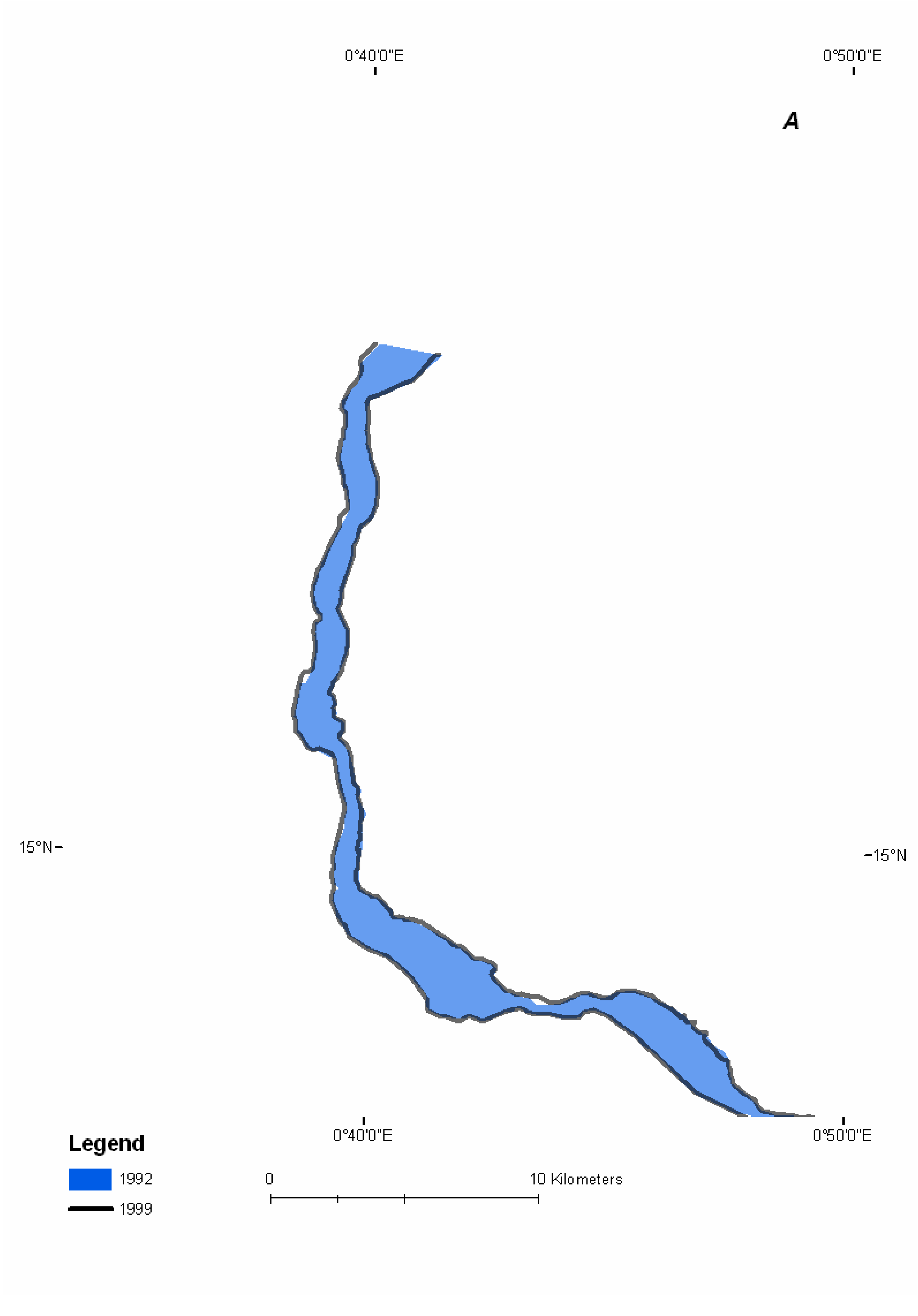


Figure B- 4A: Channel change in Reach 1 (1992-1999)

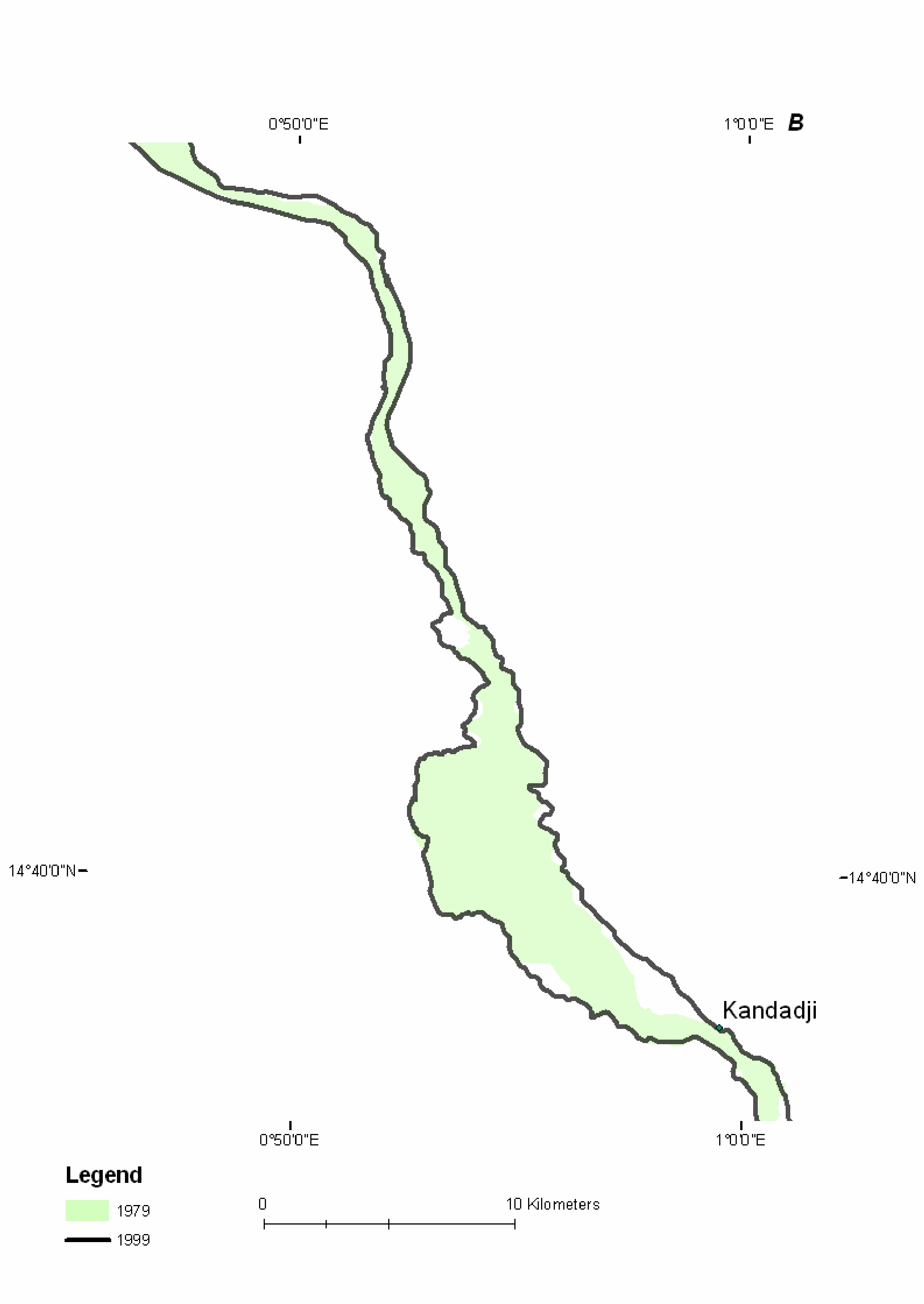


Figure B- 5B: Channel change in Reach 1 (1979-1999)

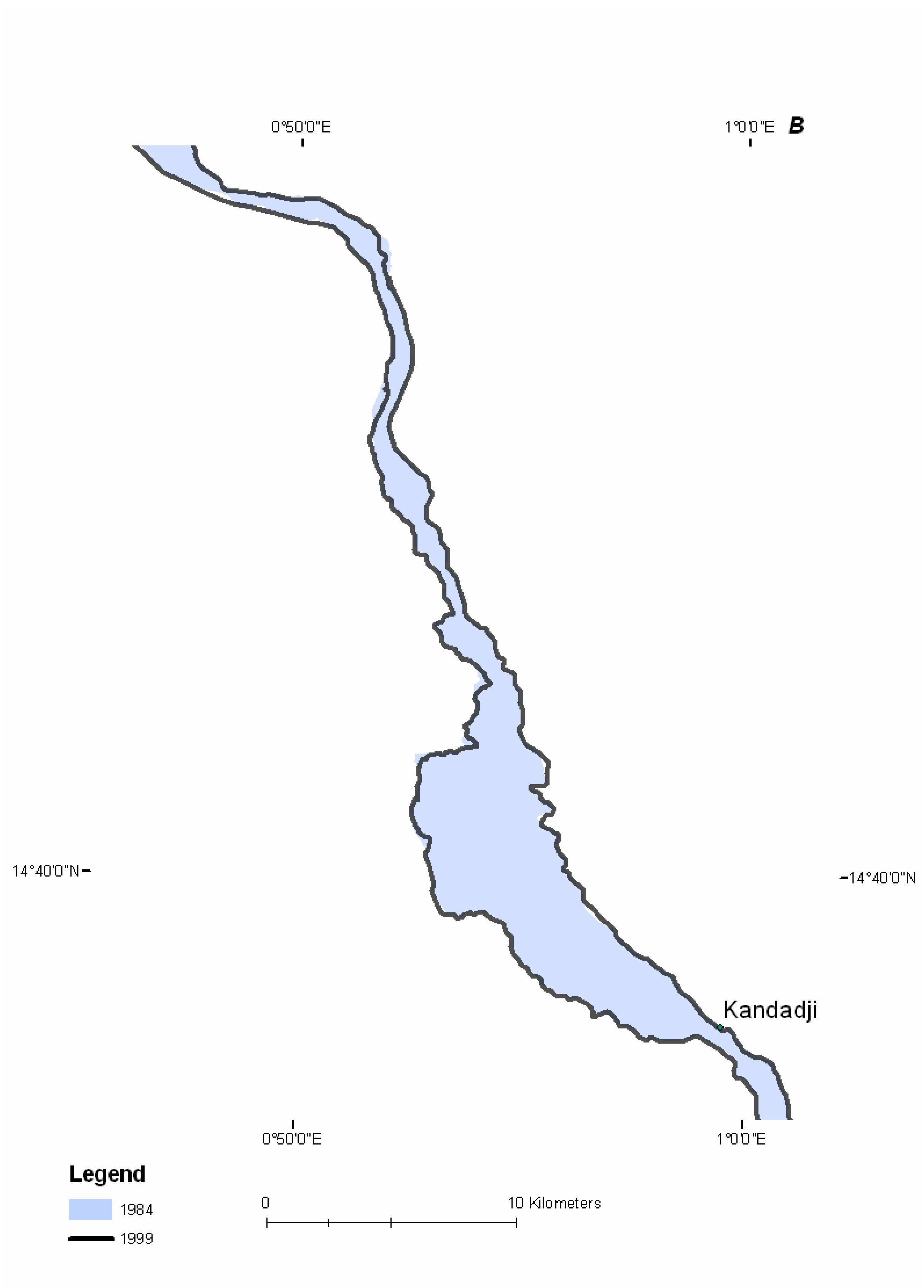


Figure B- 6B: Channel change in Reach 1 (1984-1999)

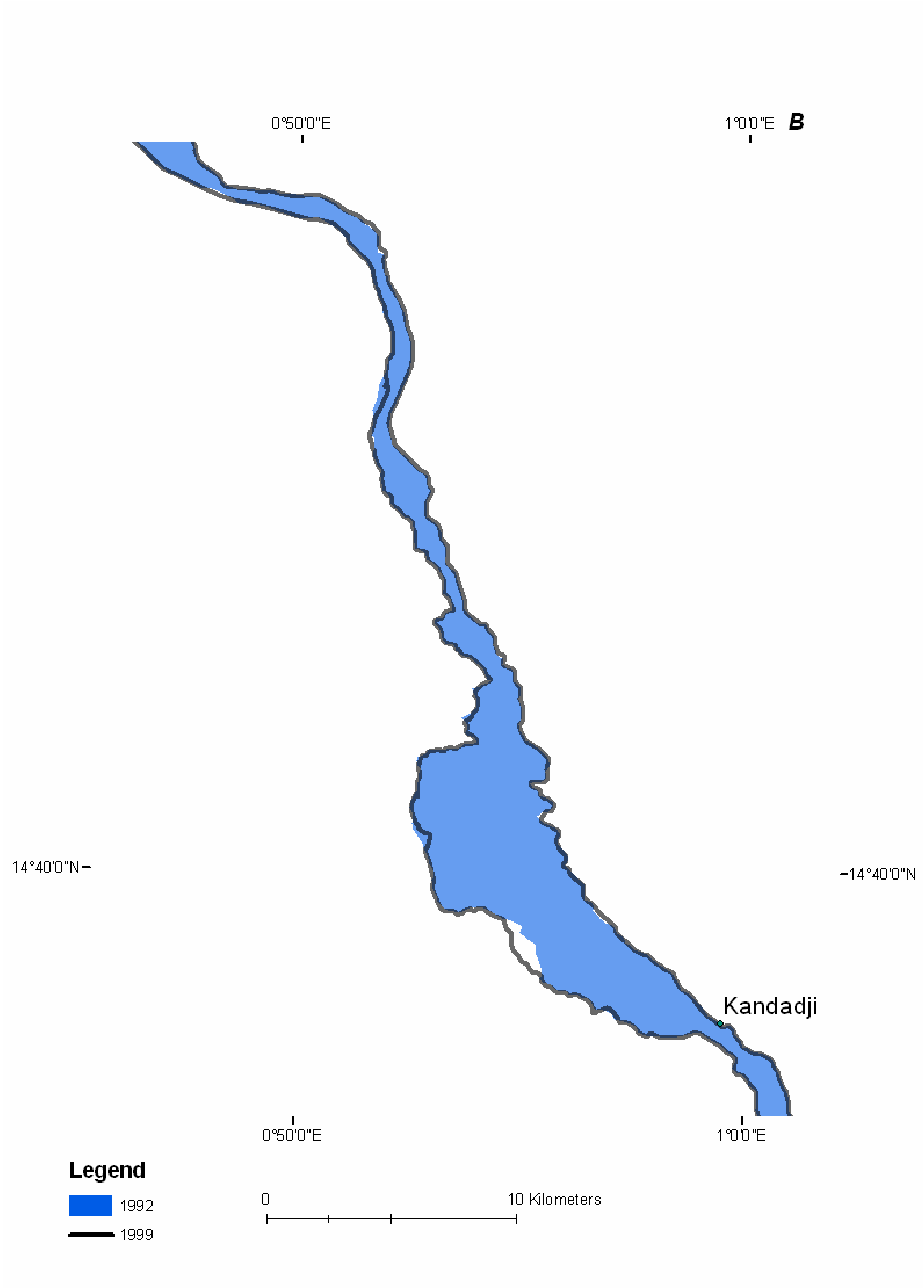


Figure B- 7B: Channel change in Reach 1 (1992-1999)

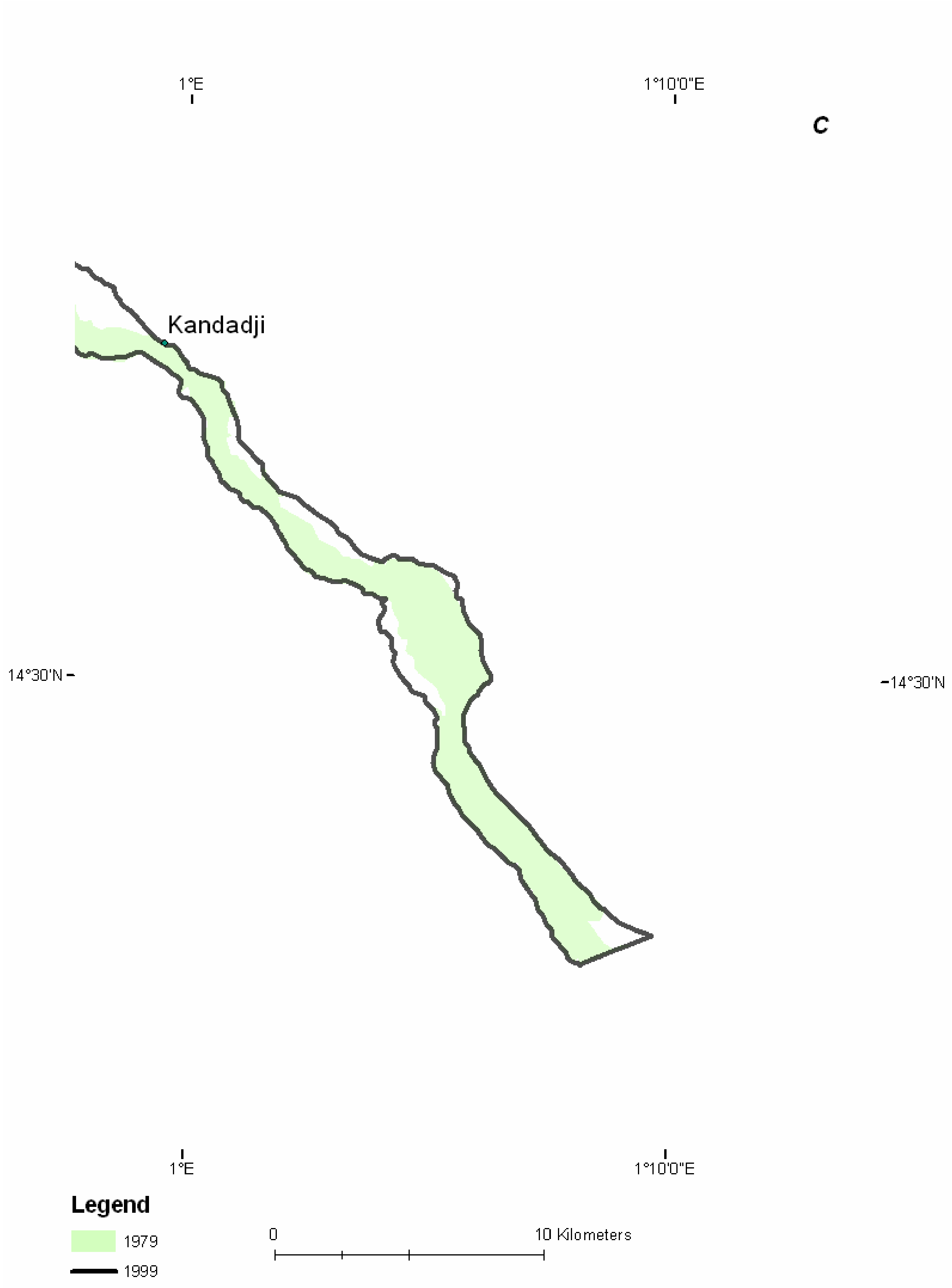


Figure B- 8C: Channel change in Reach 1 (1979-1999)

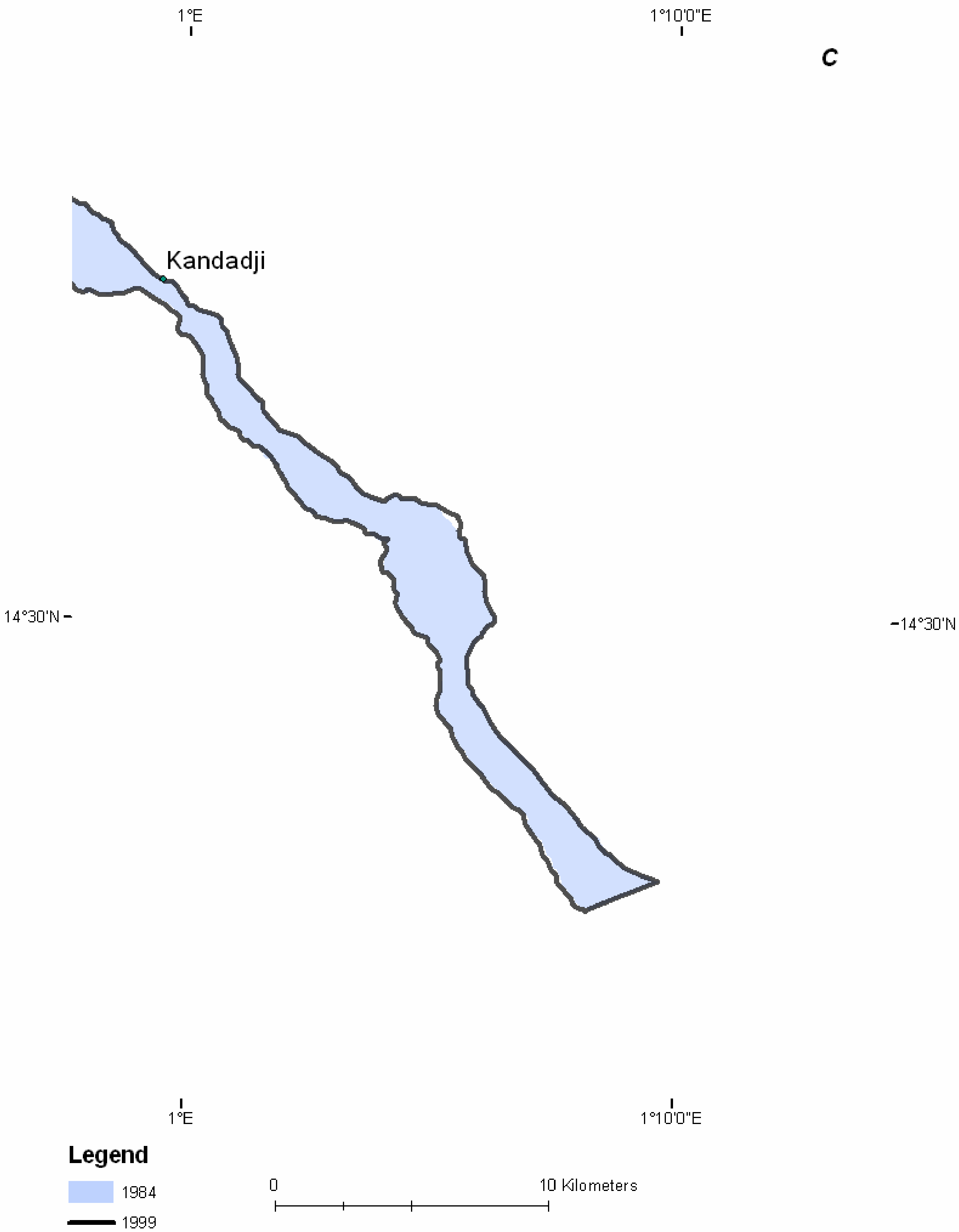


Figure B- 9C: Channel change in Reach 1 (1984-1999)

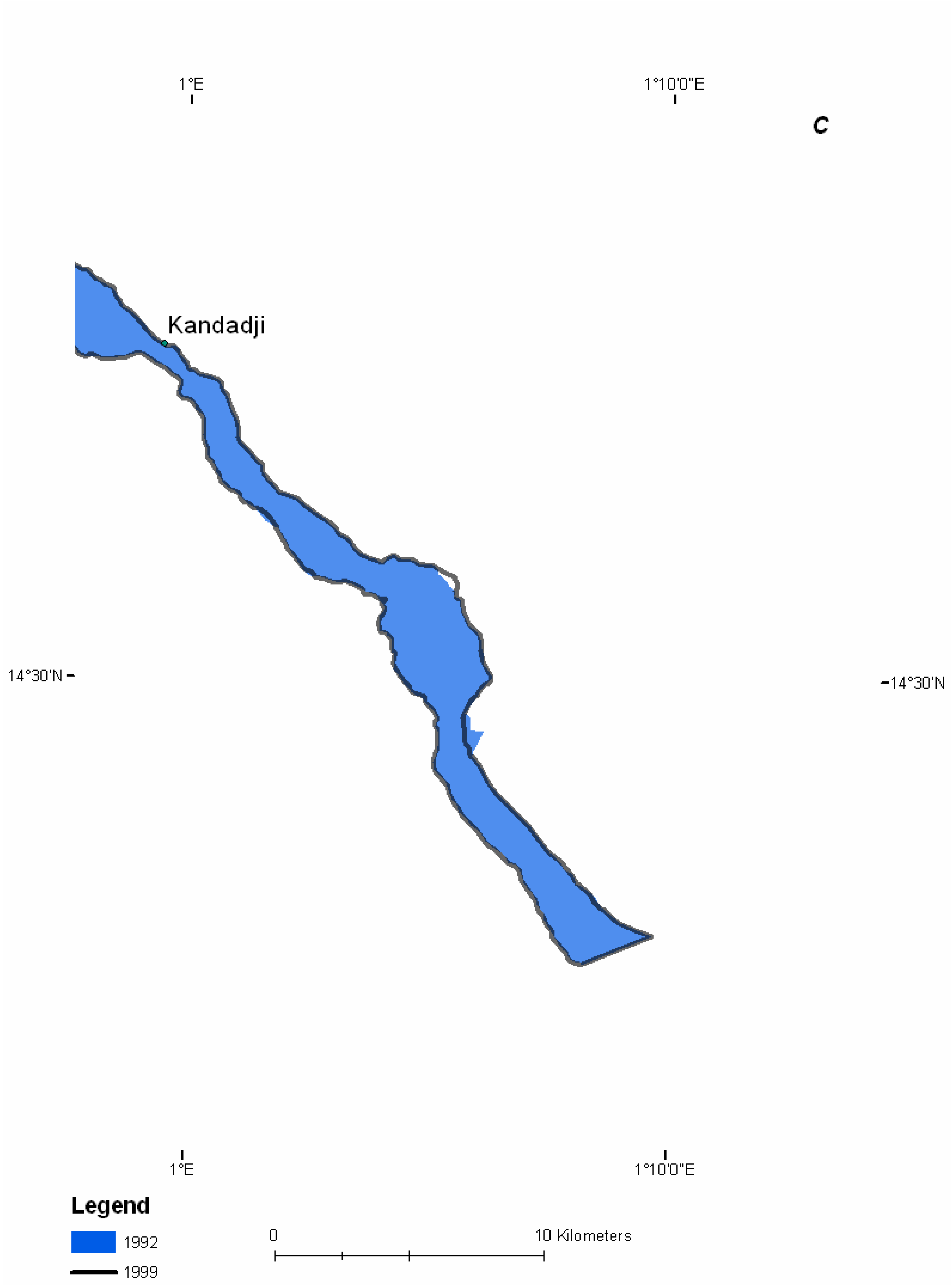


Figure B- 10C: Channel change in Reach 1 (1992-1999)

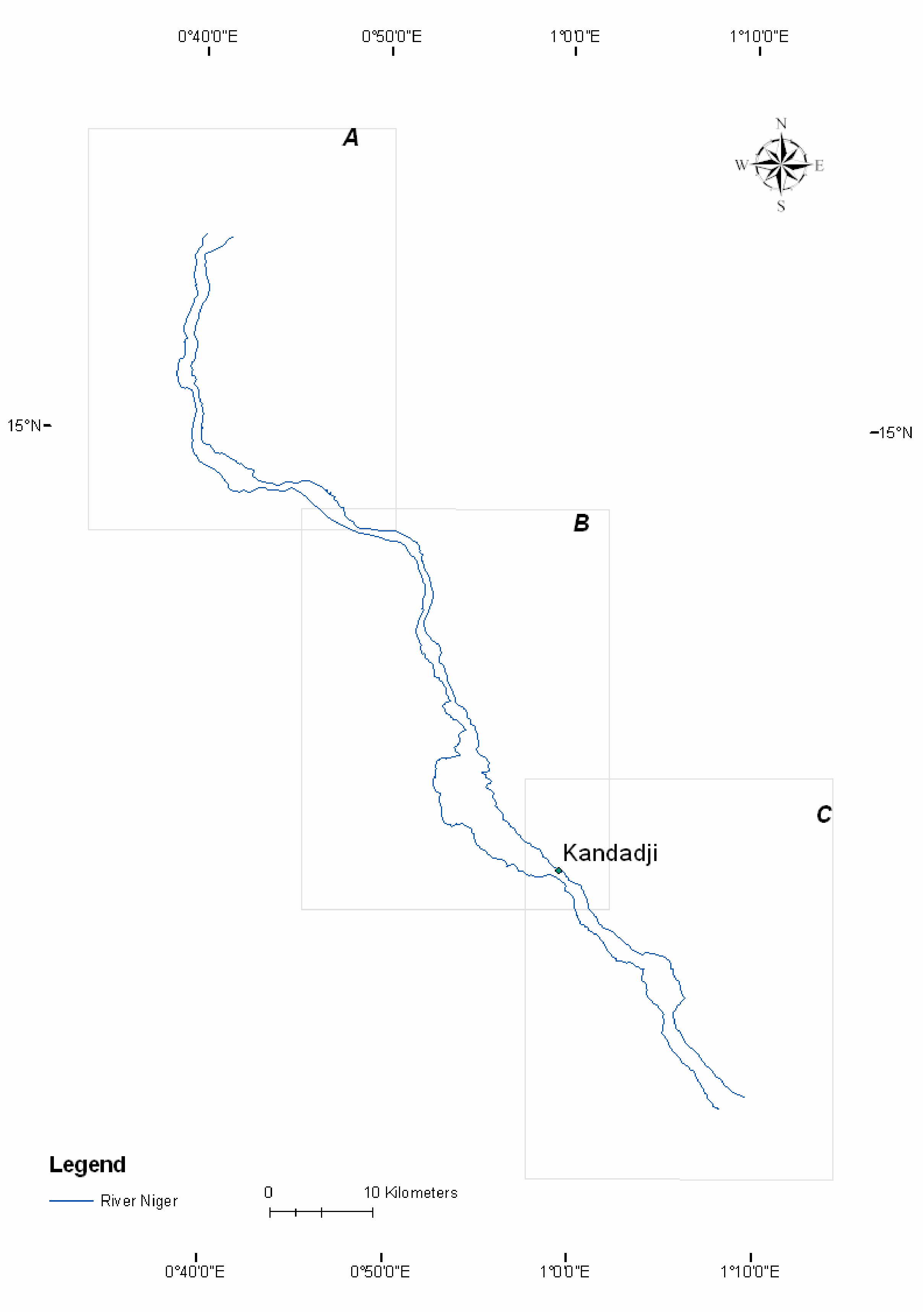


Figure B- 11: Reach 1

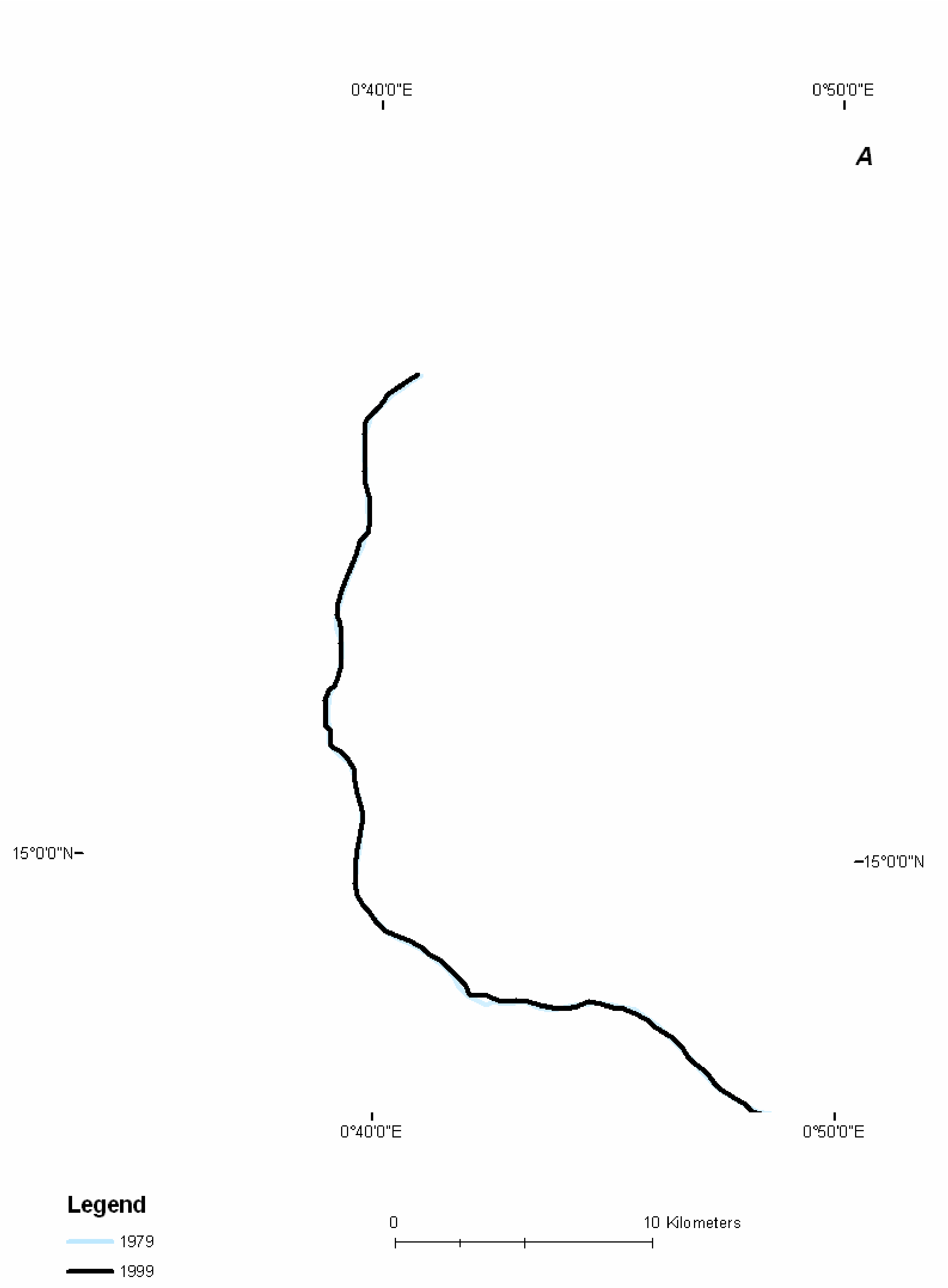


Figure B- 12A: River centre line change in reach 1 (1979 – 1999)

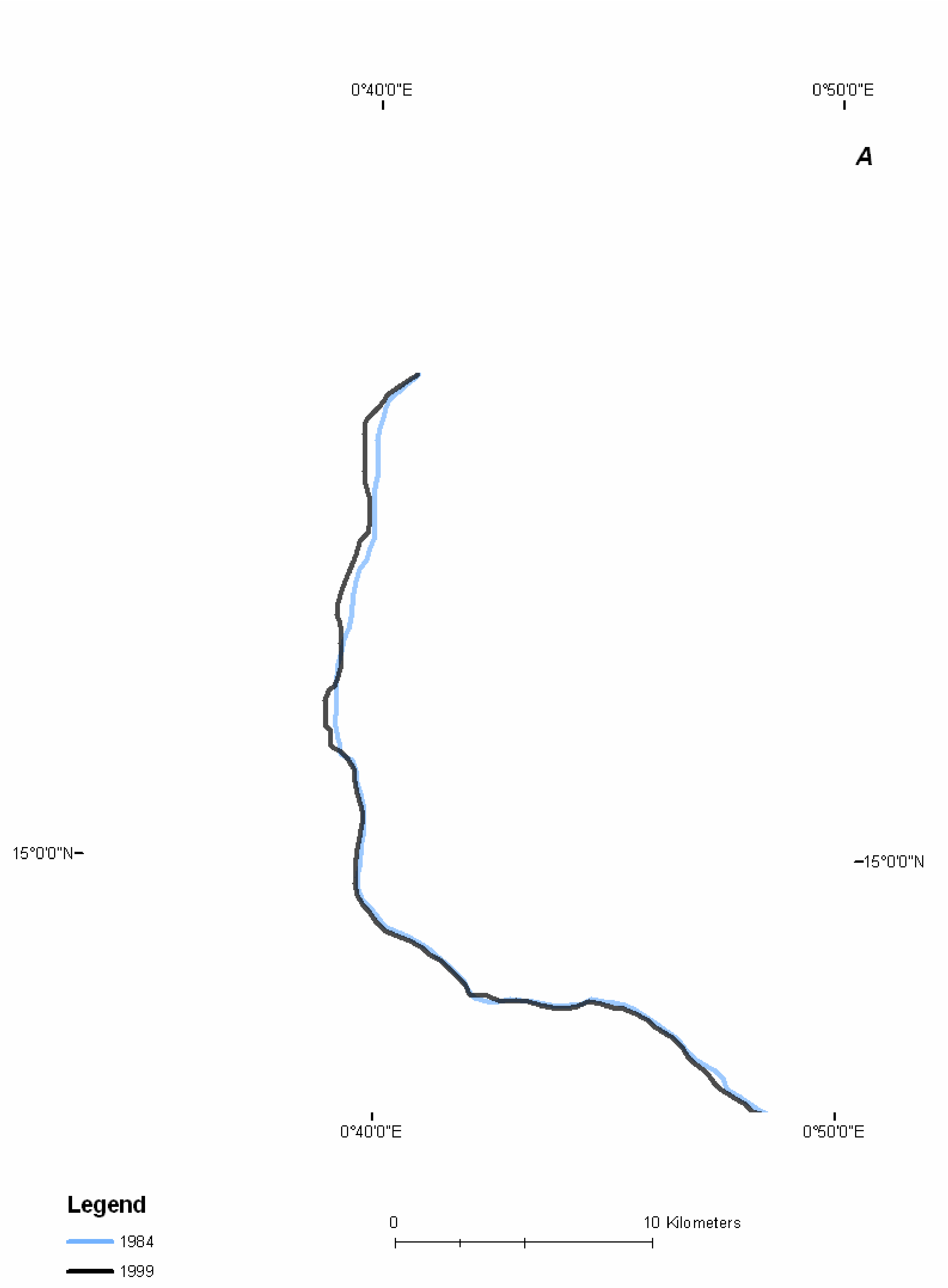


Figure B- 13A: River centre line change in reach 1 (1984 – 1999)

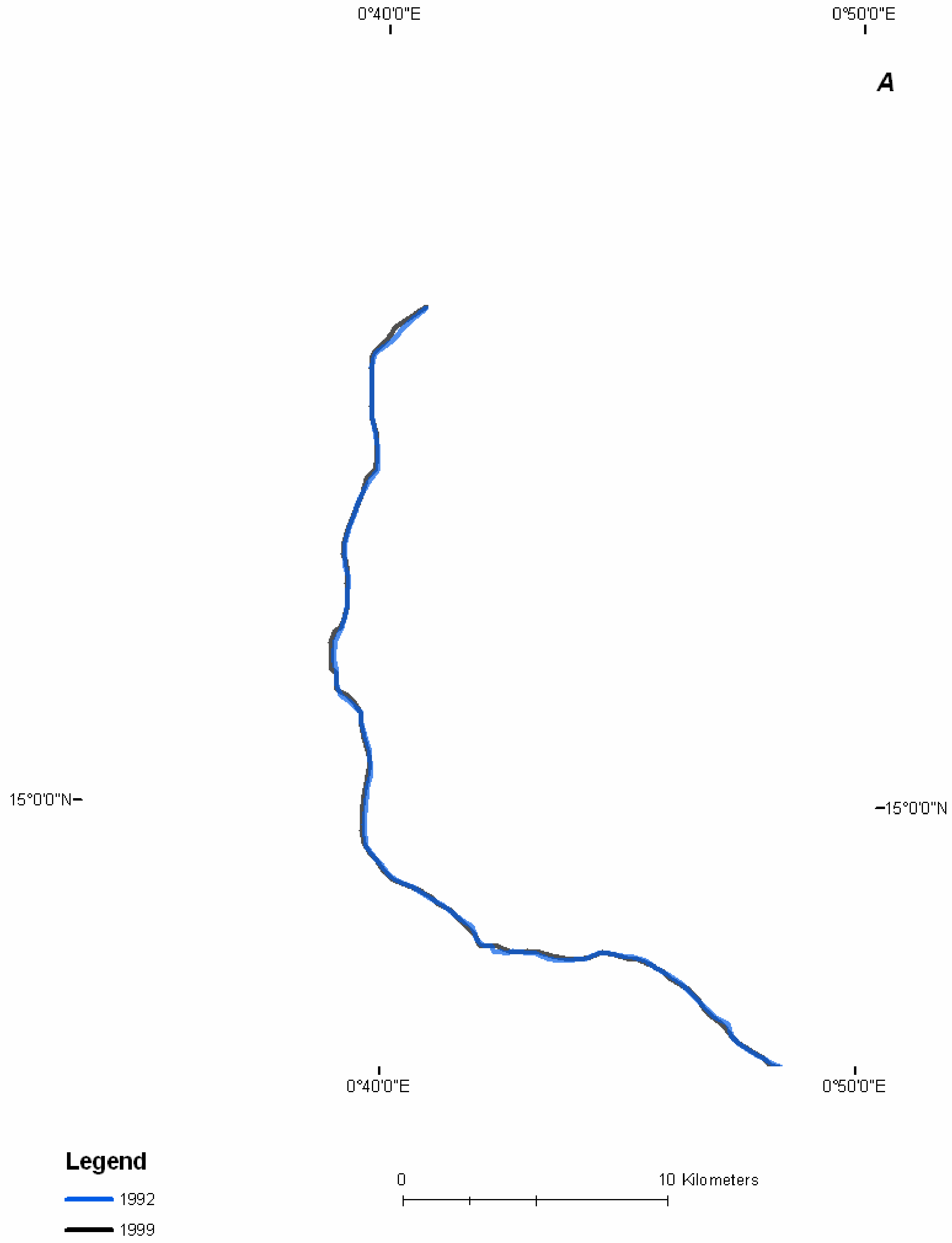


Figure B- 14A: River centre line change in reach 1 (1992 – 1999)

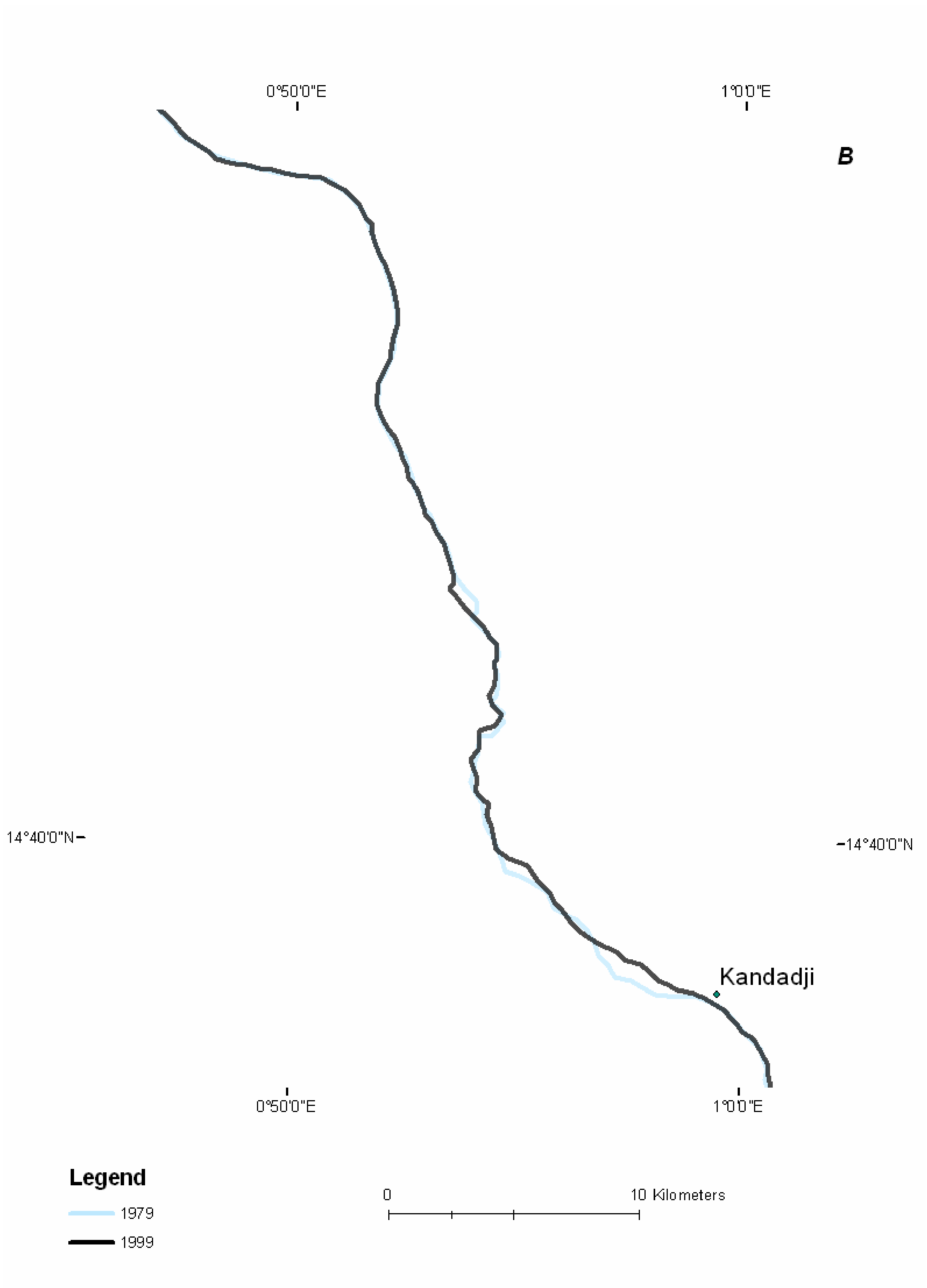


Figure B- 15B: River centre line change in reach 1 (1979 – 1999)

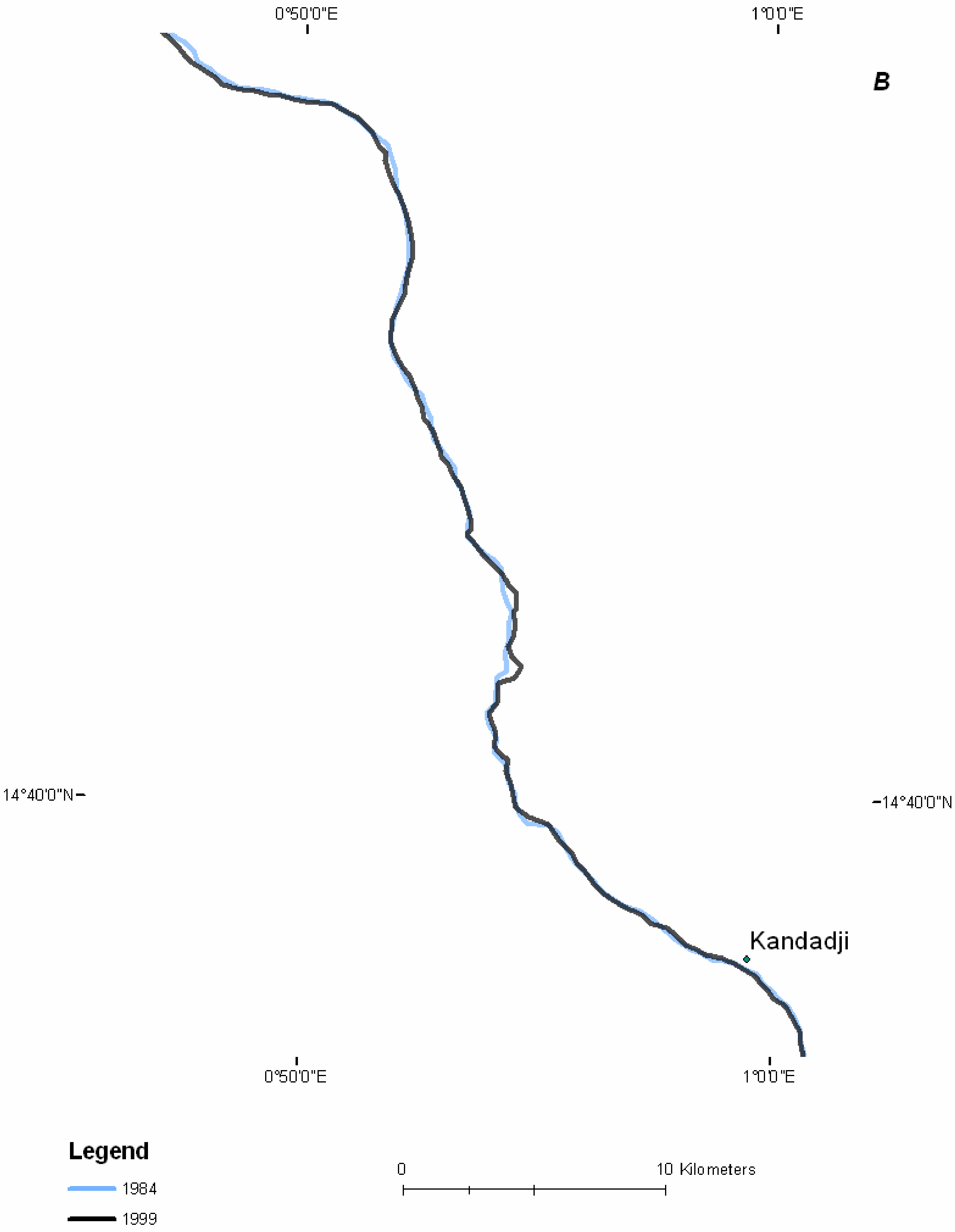


Figure B- 16B: River centre line change in reach 1 (1984 – 1999)

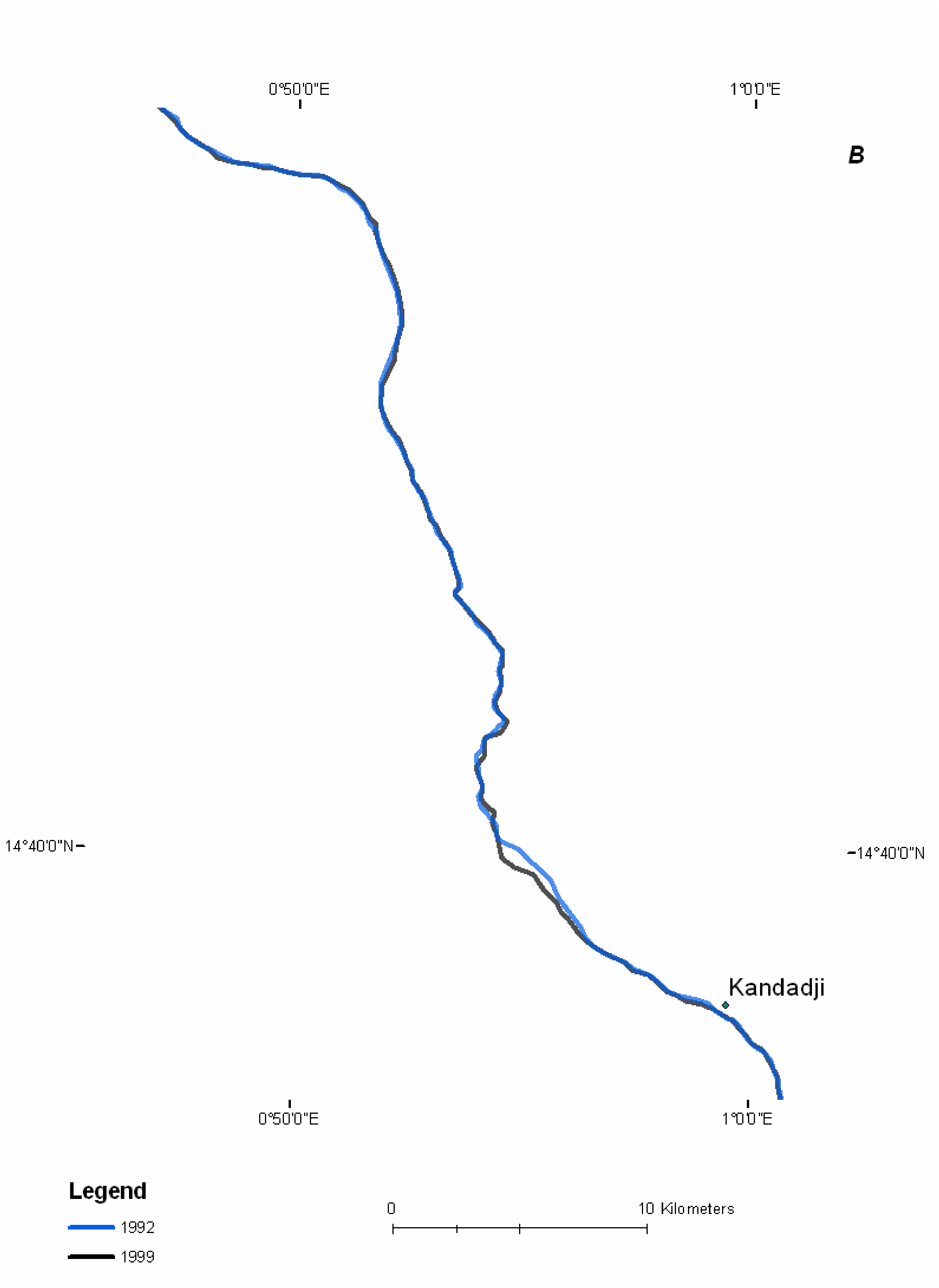


Figure B- 17B: River centre line change in reach 1 (1992 – 1999)

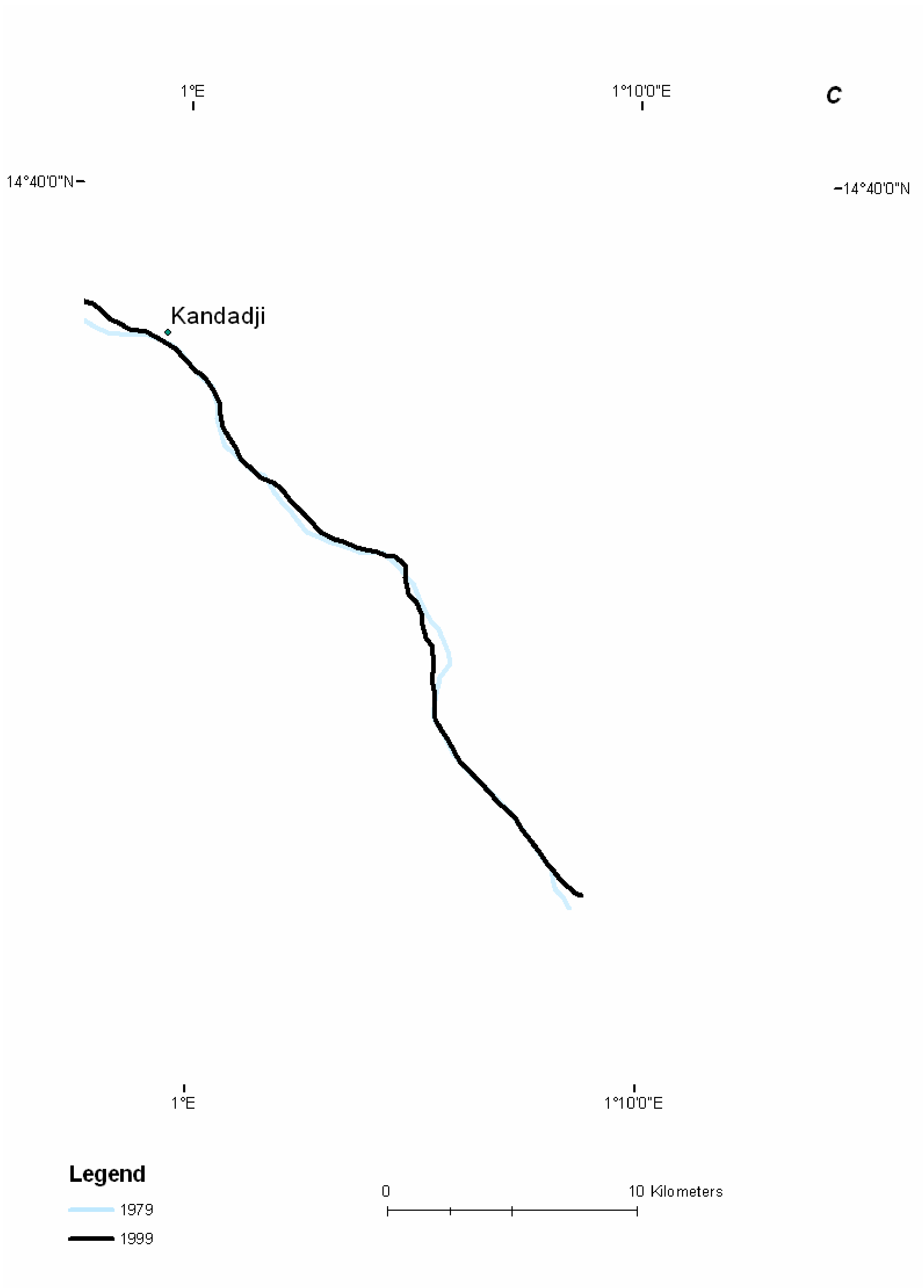


Figure B- 18C: River centre line change in reach 1 (1979 – 1999)

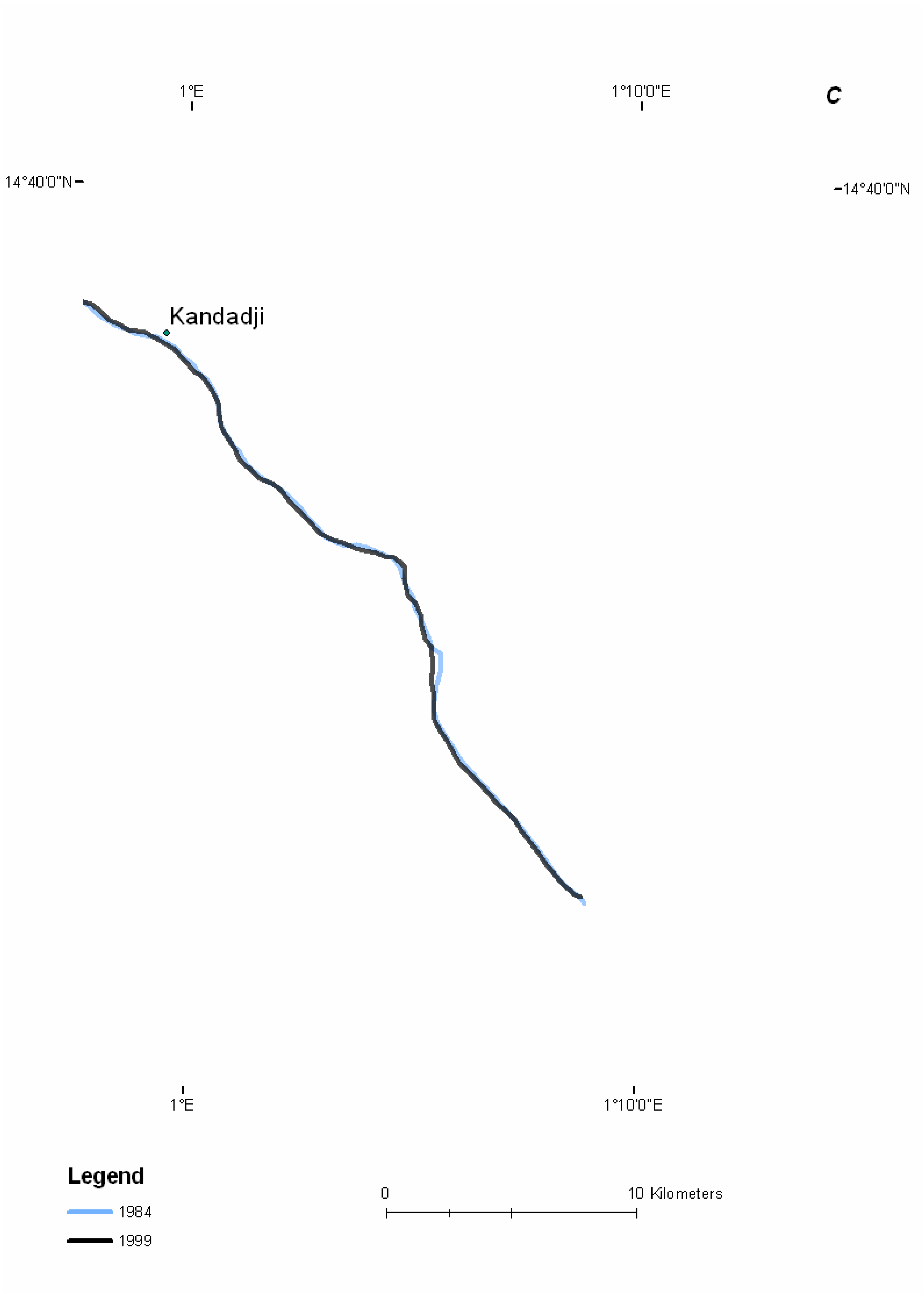


Figure B- 19C: River centre line change in reach 1 (1984 – 1999)

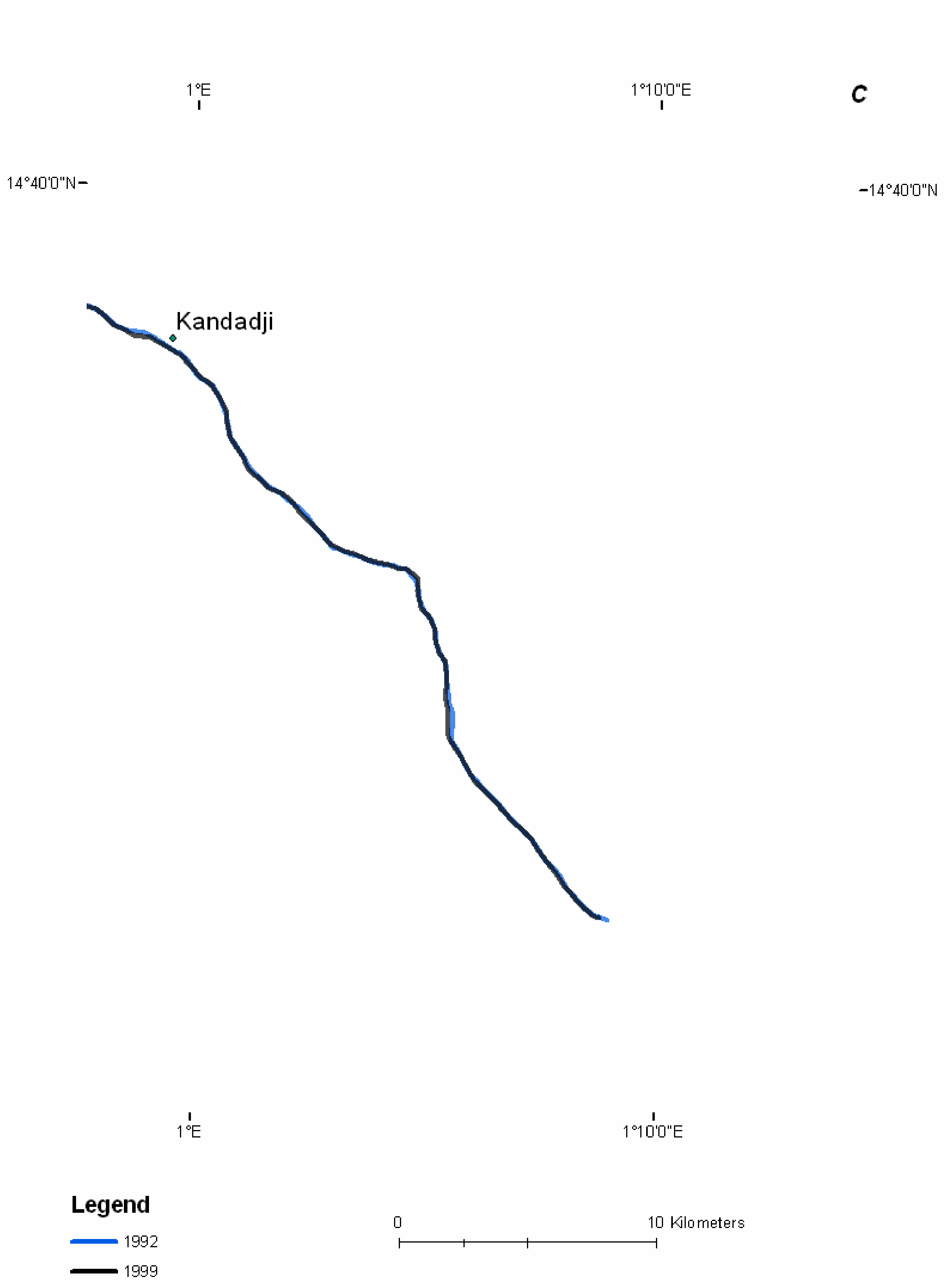


Figure B- 20C: River centre line change in reach 1 (1992 – 1999)

Figure B- 21A: Reach 1 channel bank and island extents in 1979

Figure B- 22A: Reach 1 channel bank and island extents in 1984

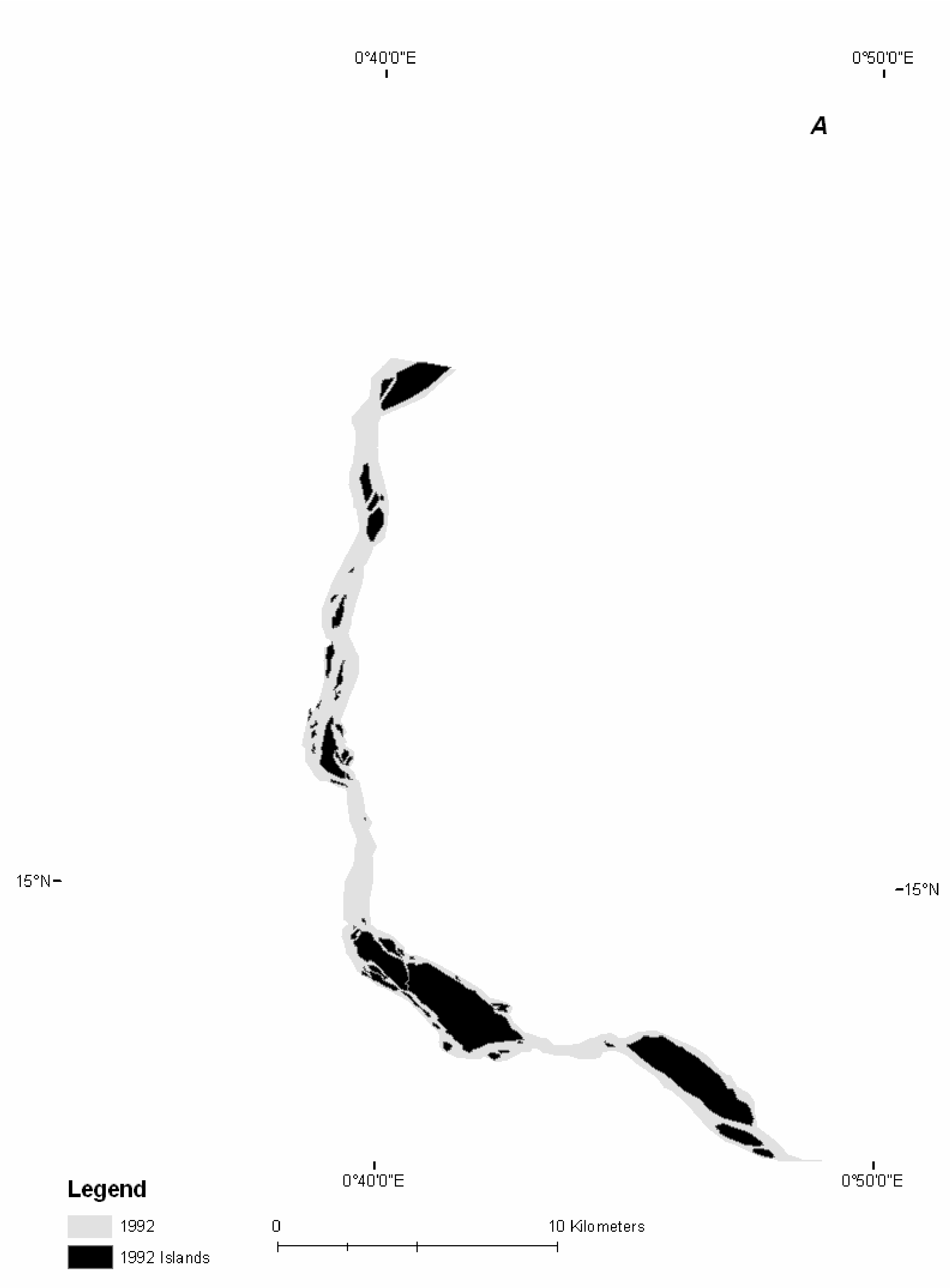


Figure B- 23A: Reach 1 channel bank and island extents in 1992

Figure B- 24A: Reach 1 channel bank and island extents in 1999

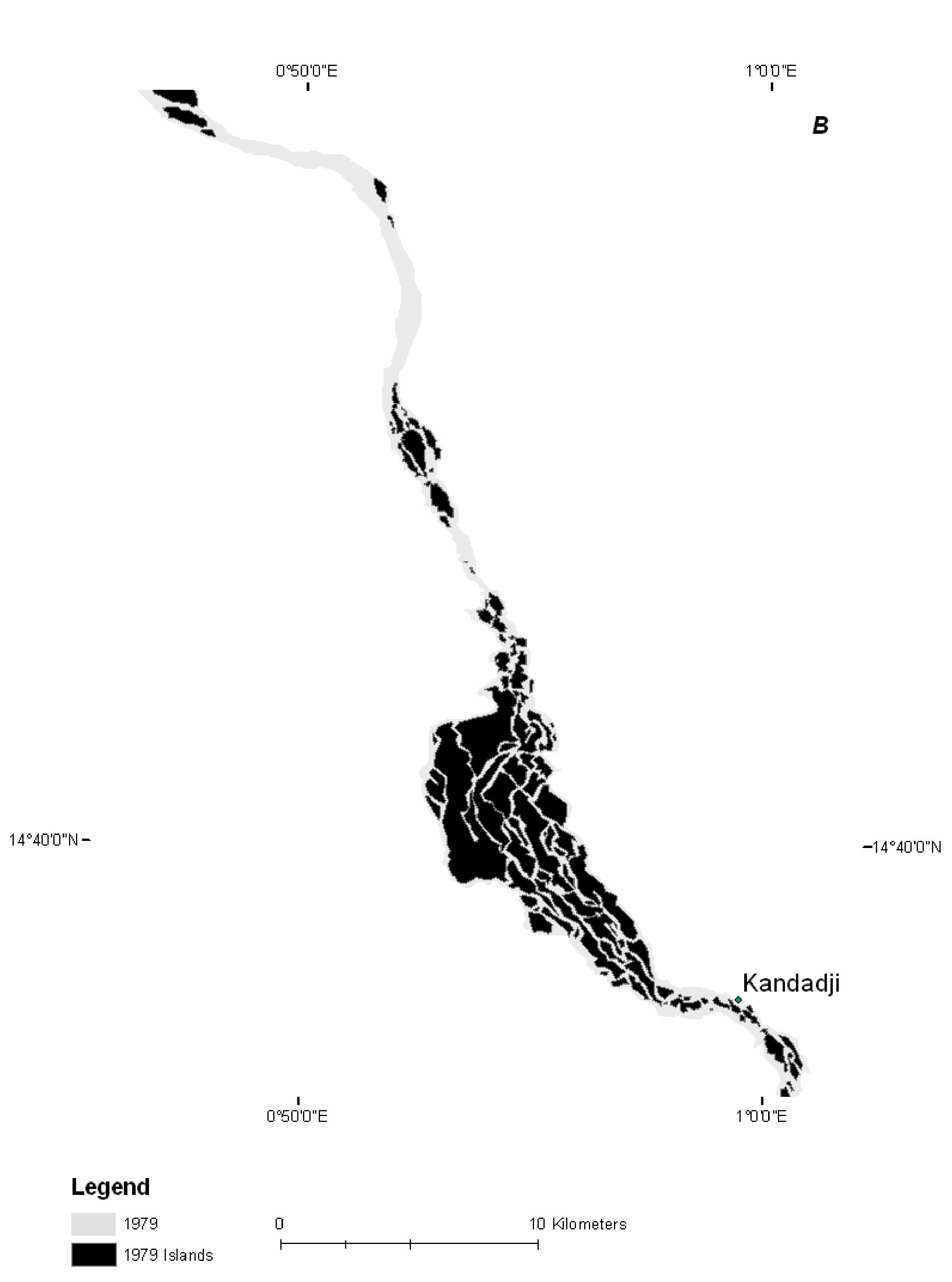


Figure B- 25B: Reach 1 channel bank and island extents in 1979

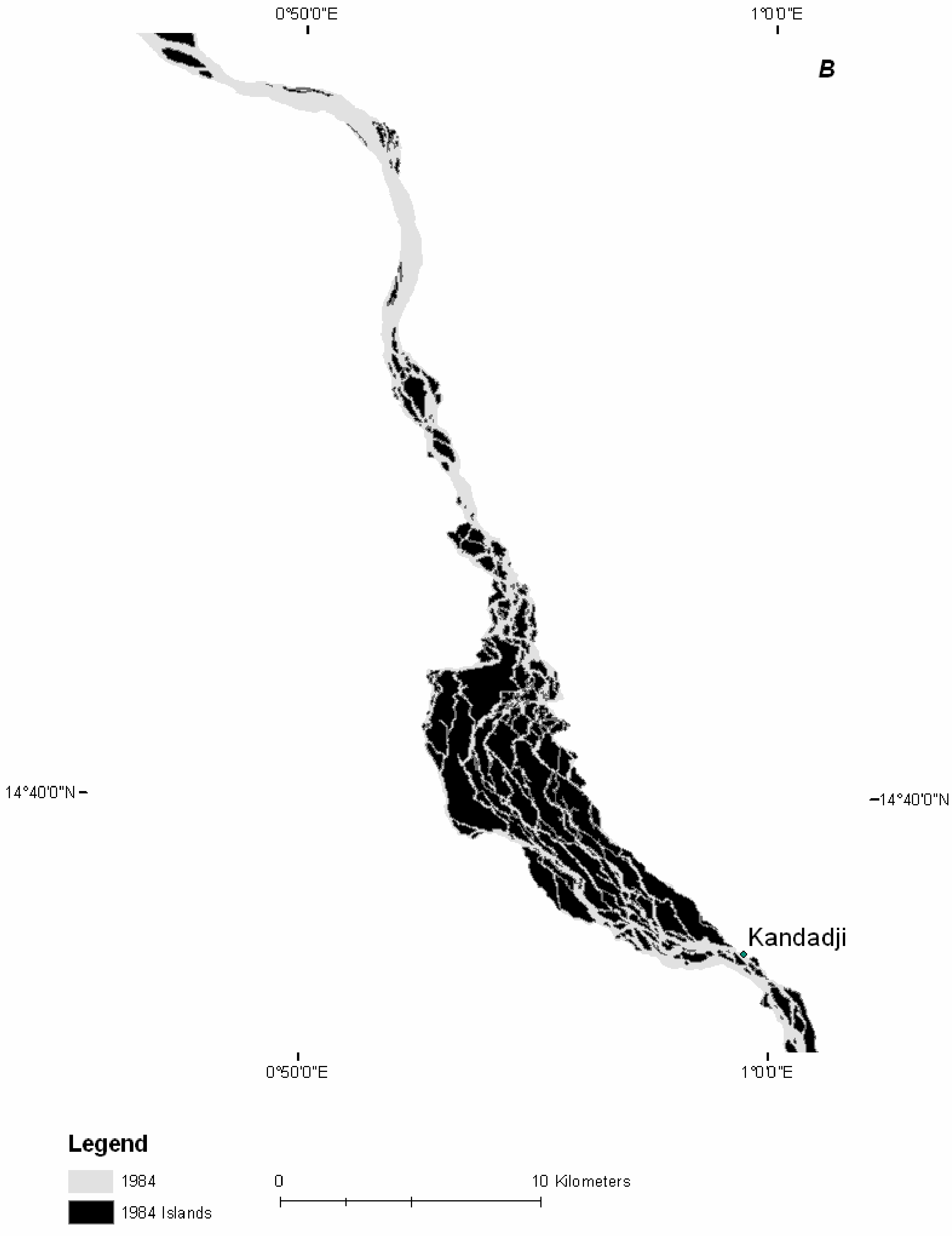


Figure B- 26B: Reach 1 channel bank and island extents in 1984

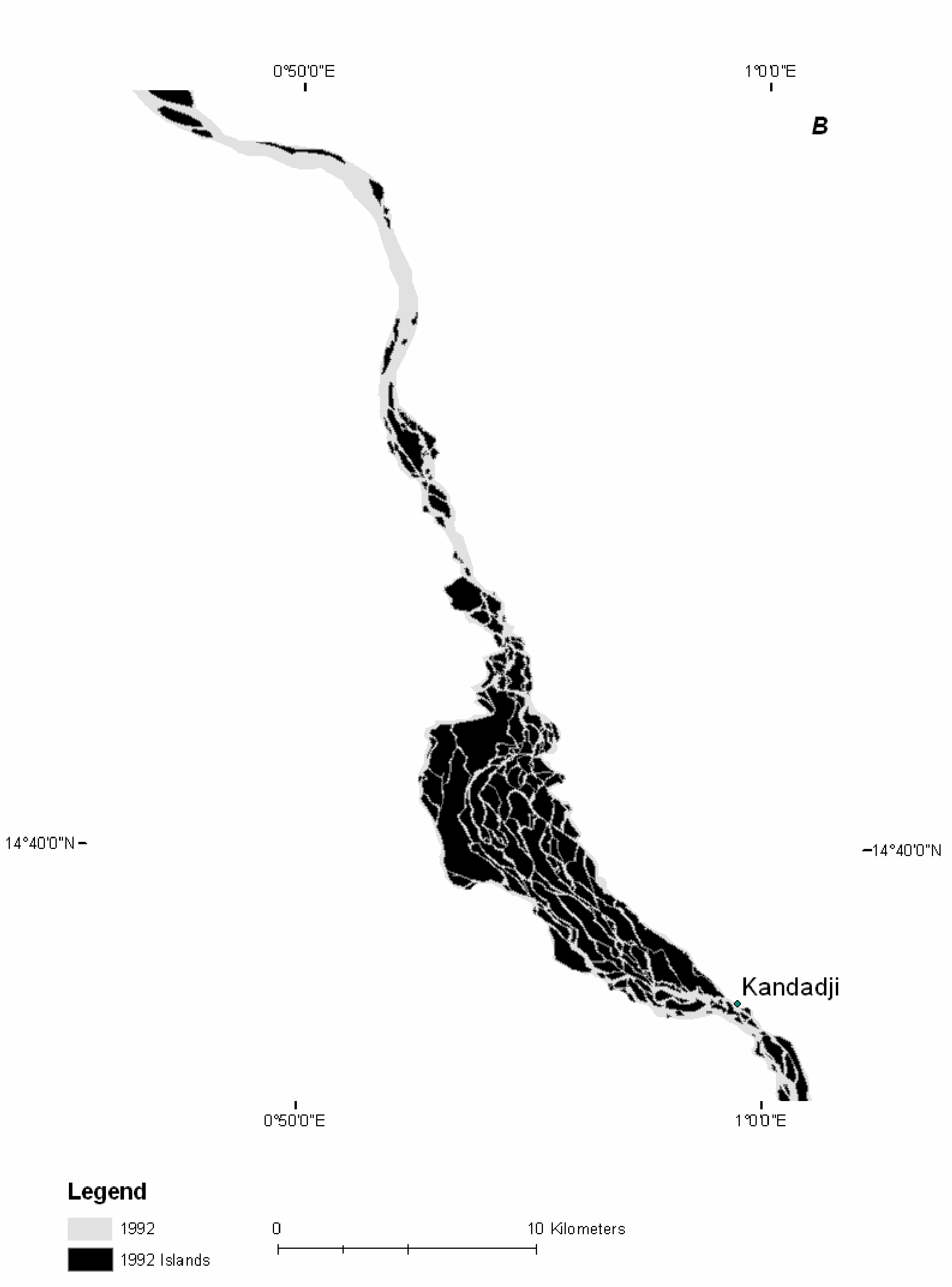


Figure B- 27B: Reach 1 channel bank and island extents in 1992

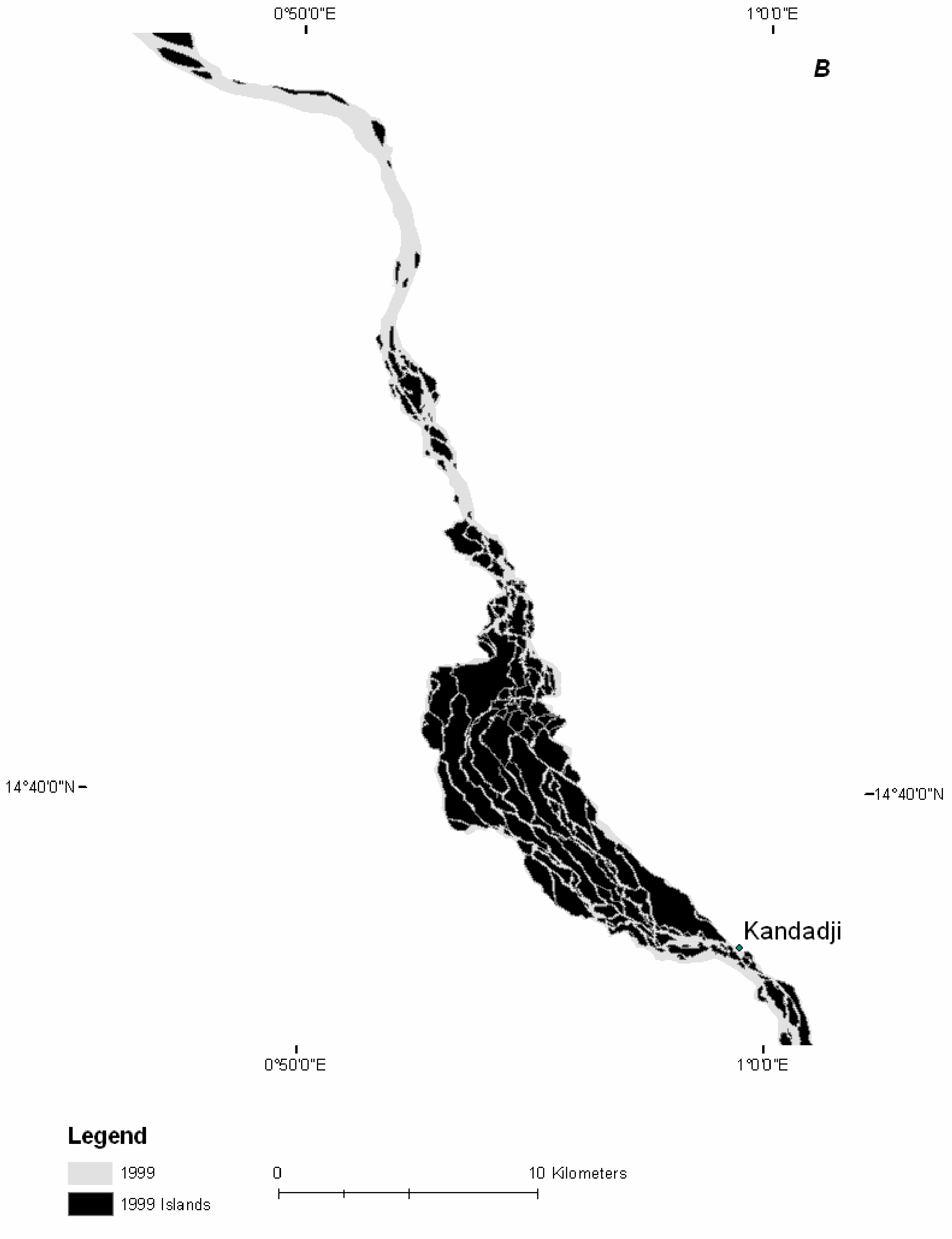


Figure B- 28B: Reach 1 channel bank and island extents in 1999

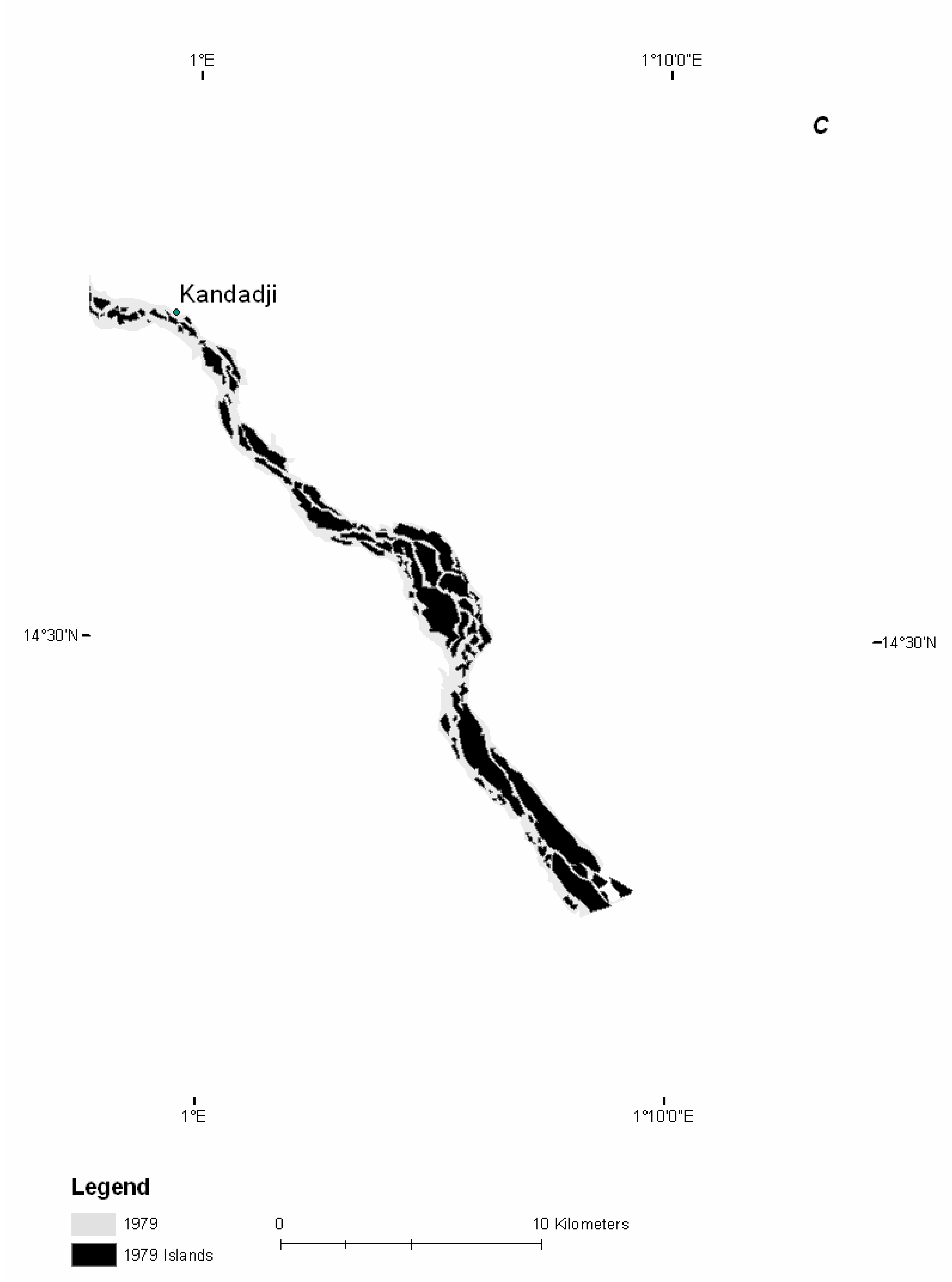


Figure B- 29C: Reach 1 channel bank and island extents in 1979

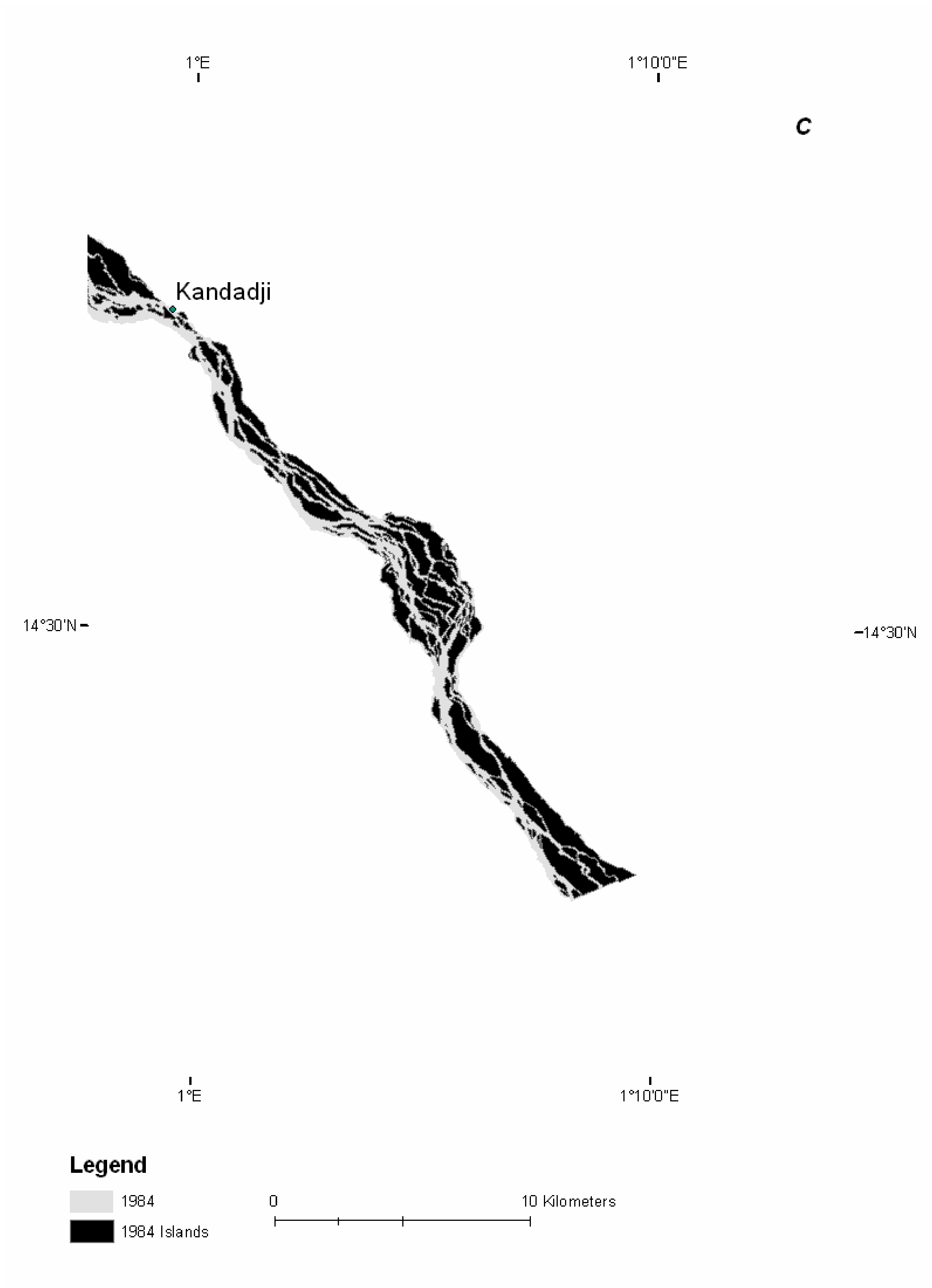


Figure B- 30C: Reach 1 channel bank and island extents in 1984

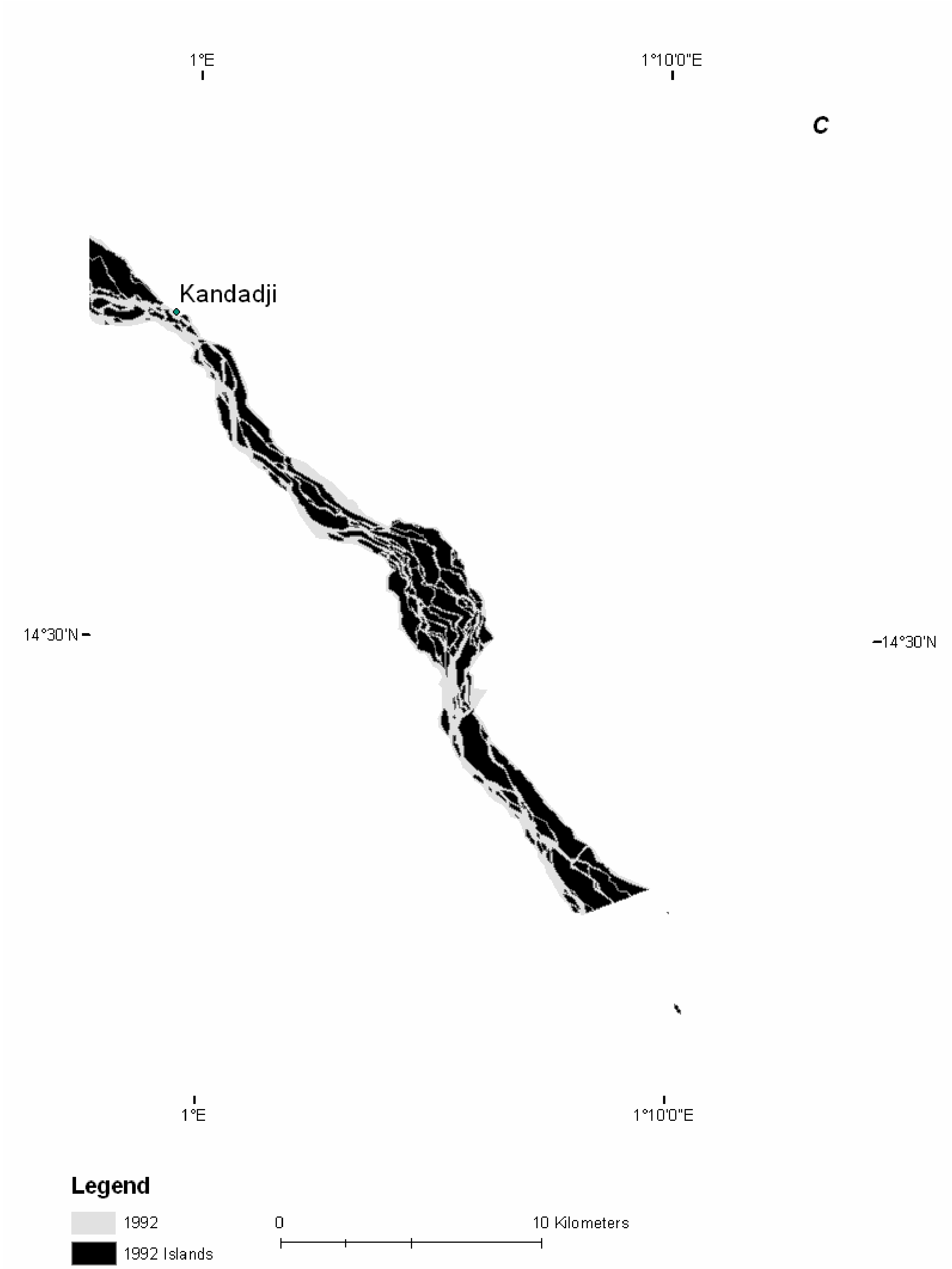


Figure B- 31C: Reach 1 channel bank and island extents in 1992

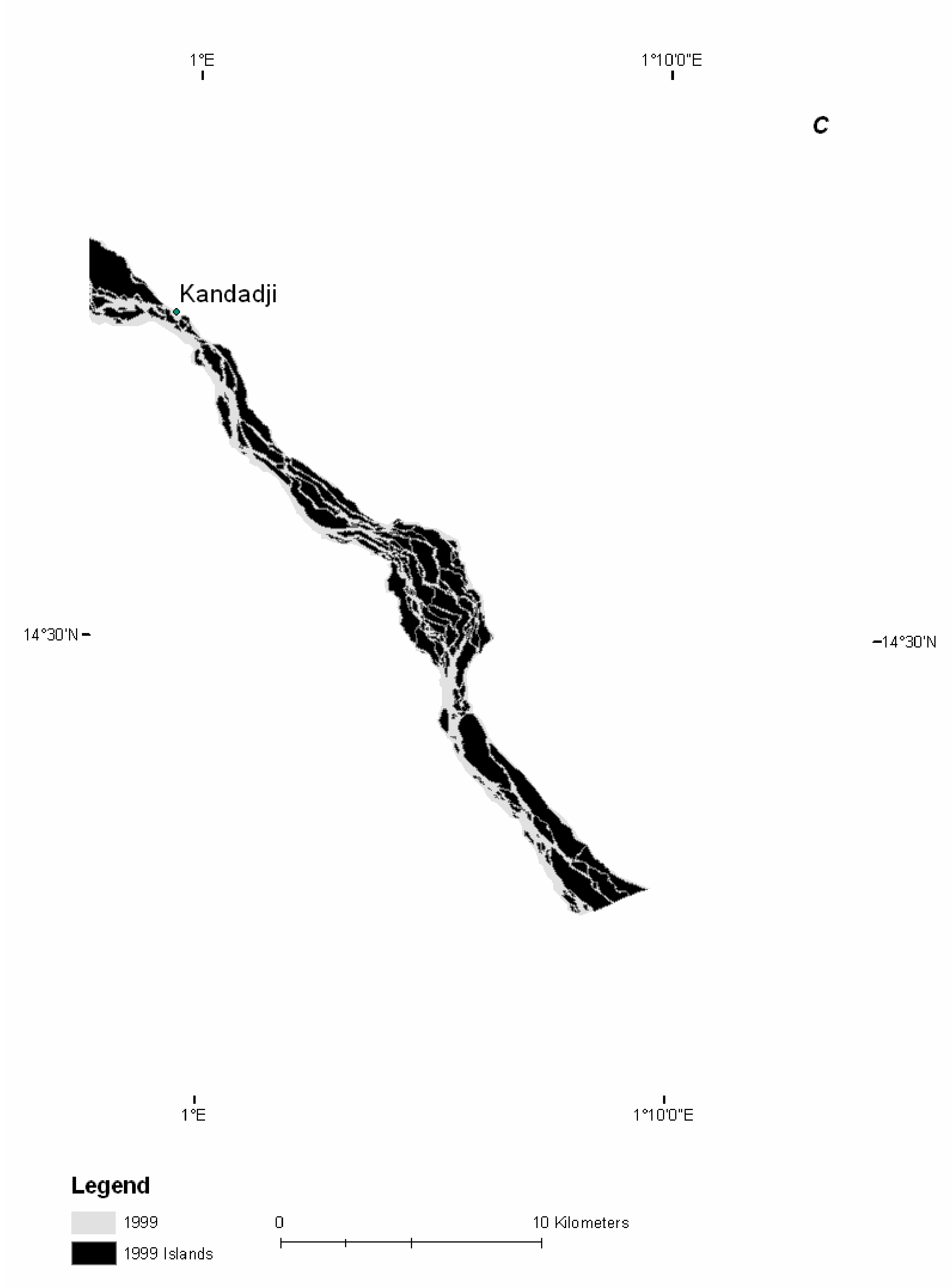


Figure B- 32C: Reach 1 channel bank and island extents in 1999

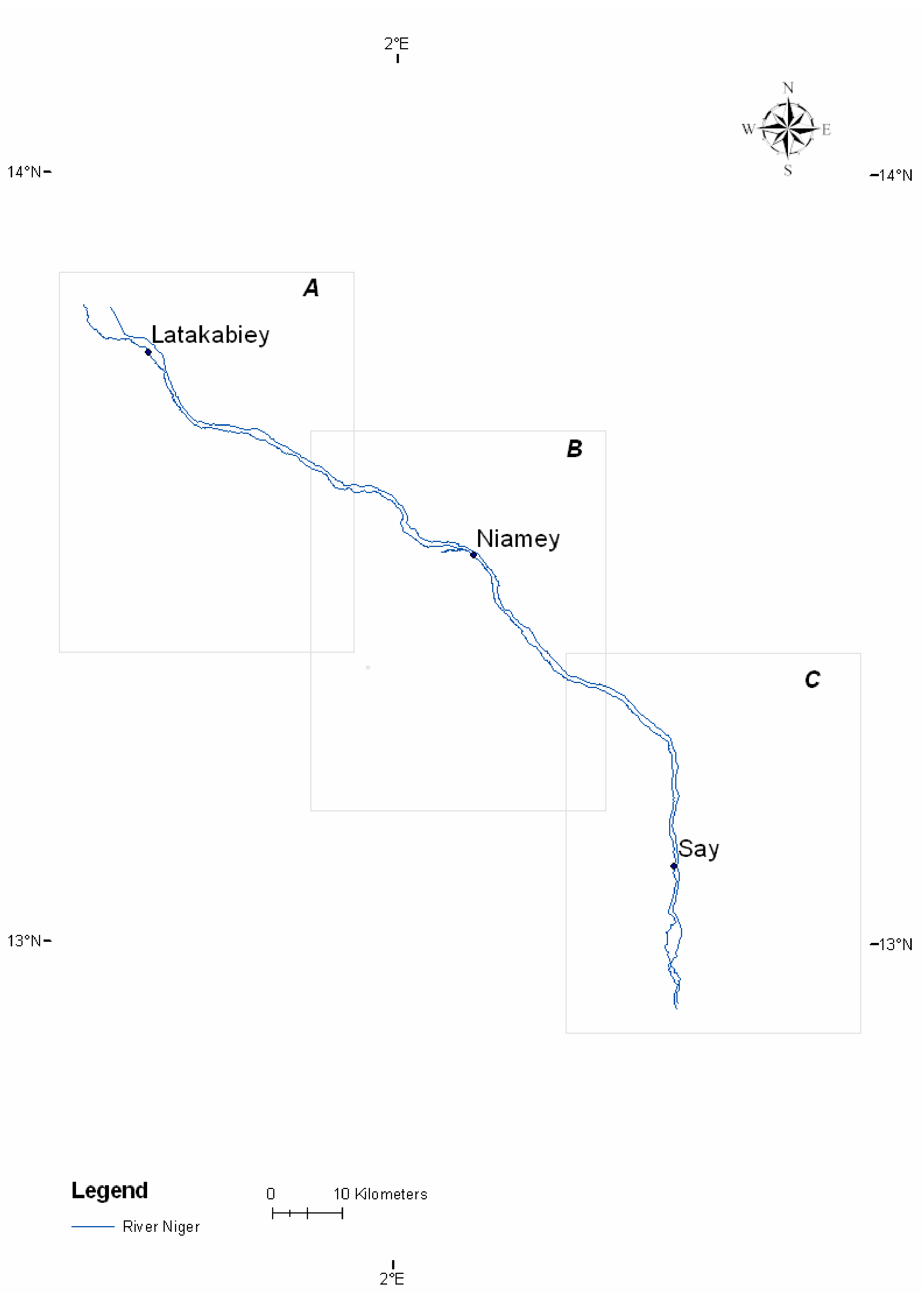


Figure B- 33 : Reach 2

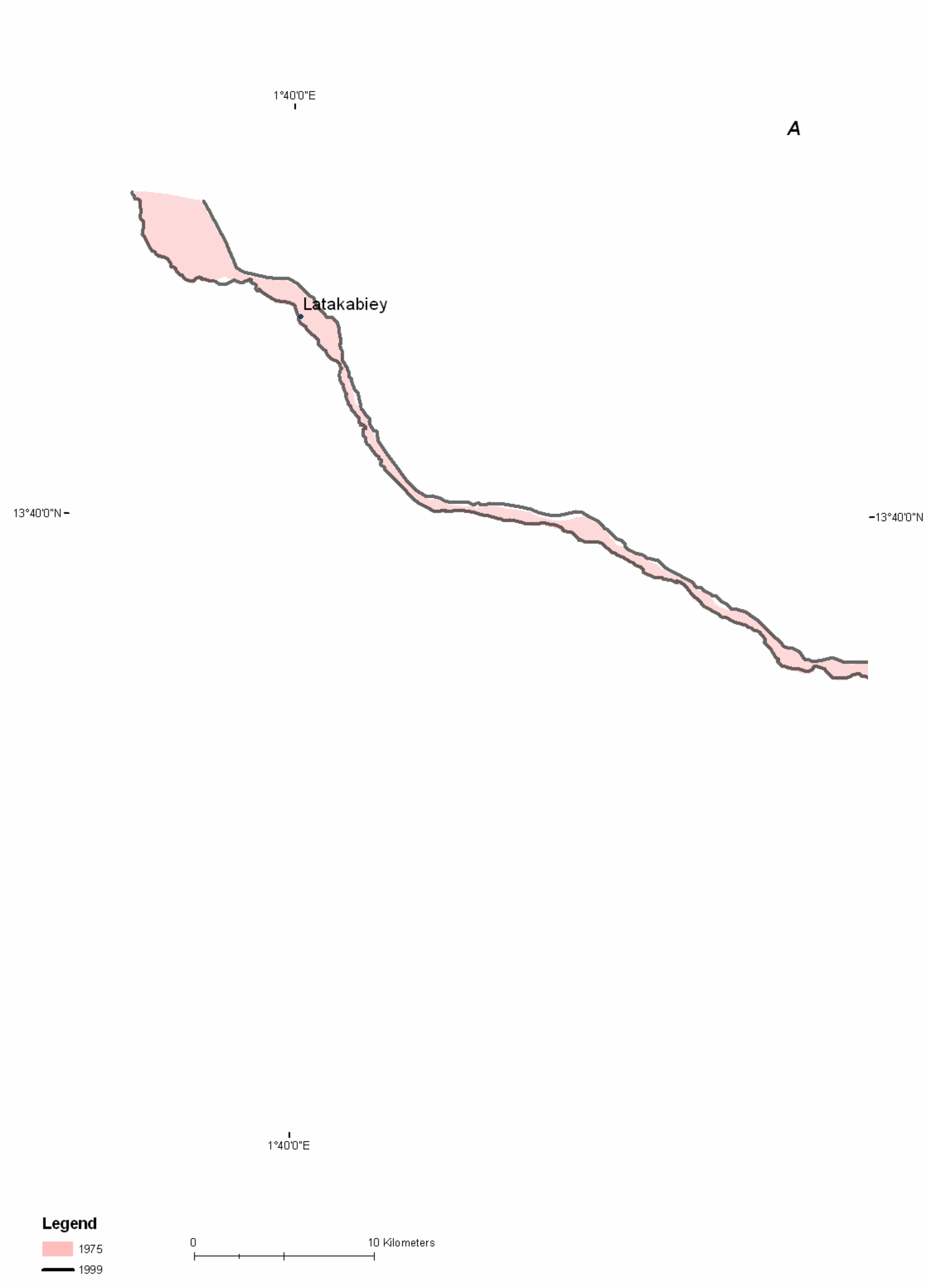


Figure B- 34A: Channel change in Reach 2 (1975-1999)

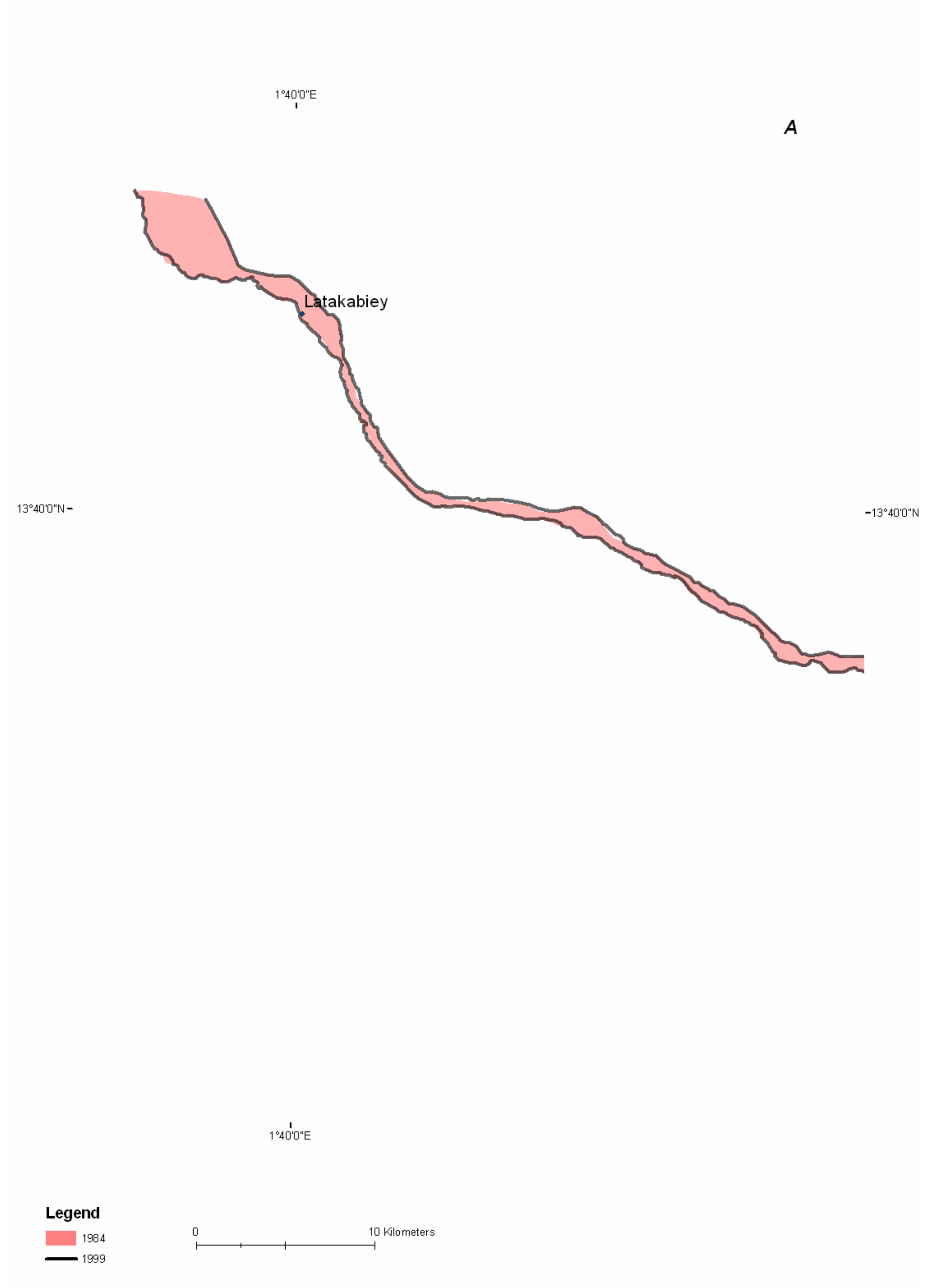


Figure B- 35A: Channel change in Reach 2 (1984-1999)

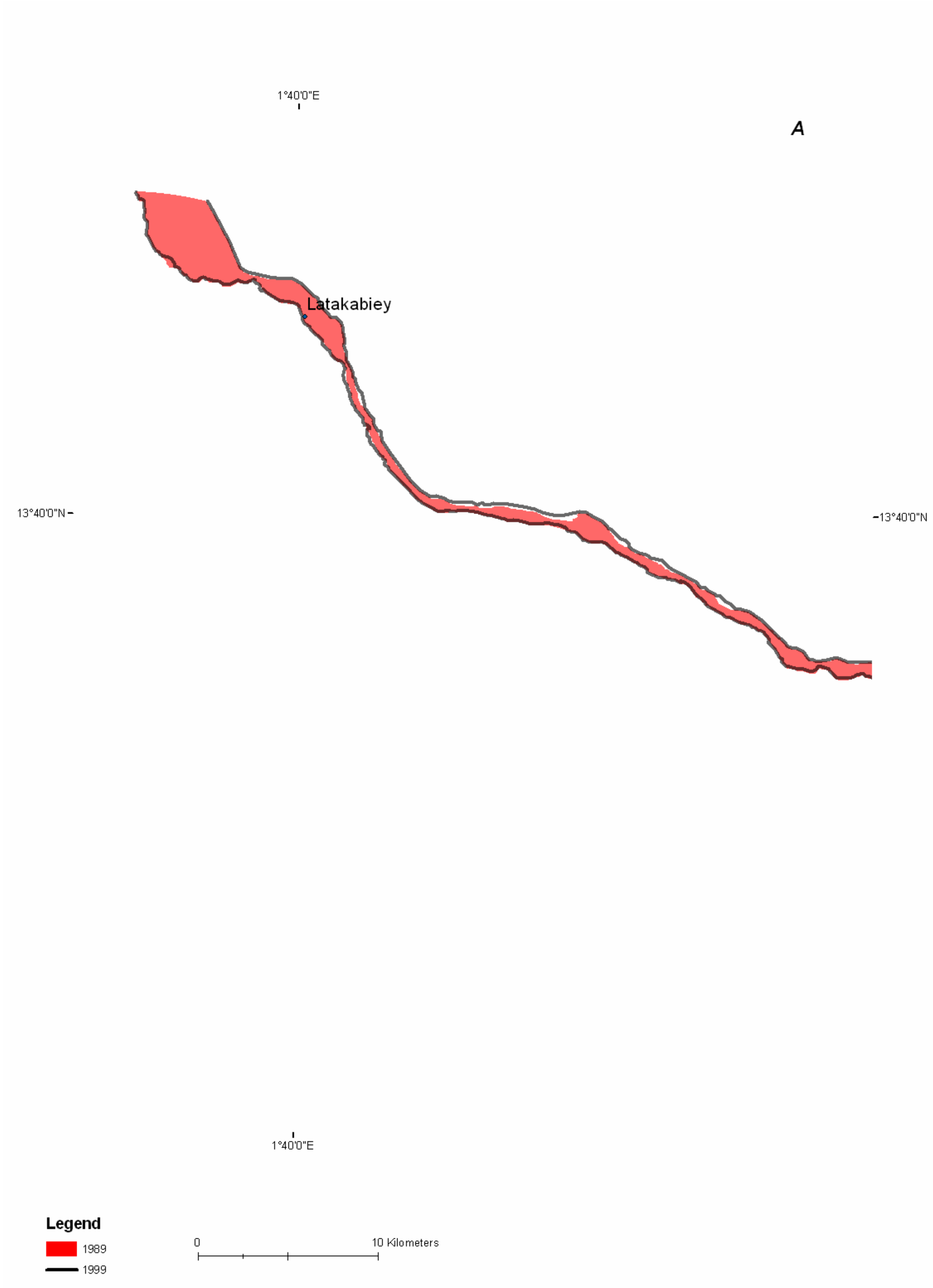


Figure B- 36A: Channel change in Reach 2 (1989-1999)

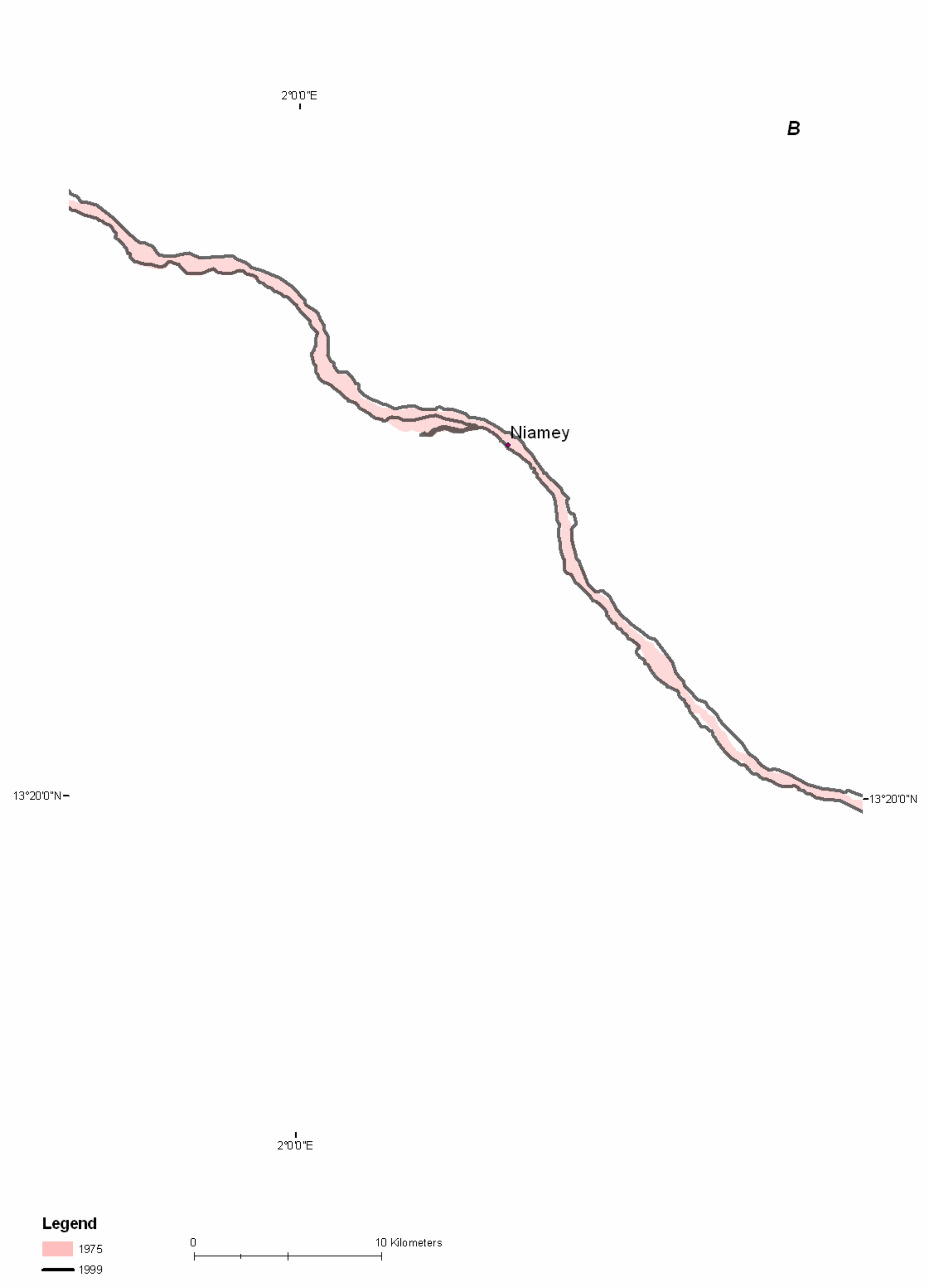


Figure B- 37B: Channel change in Reach 2 (1975-1999)

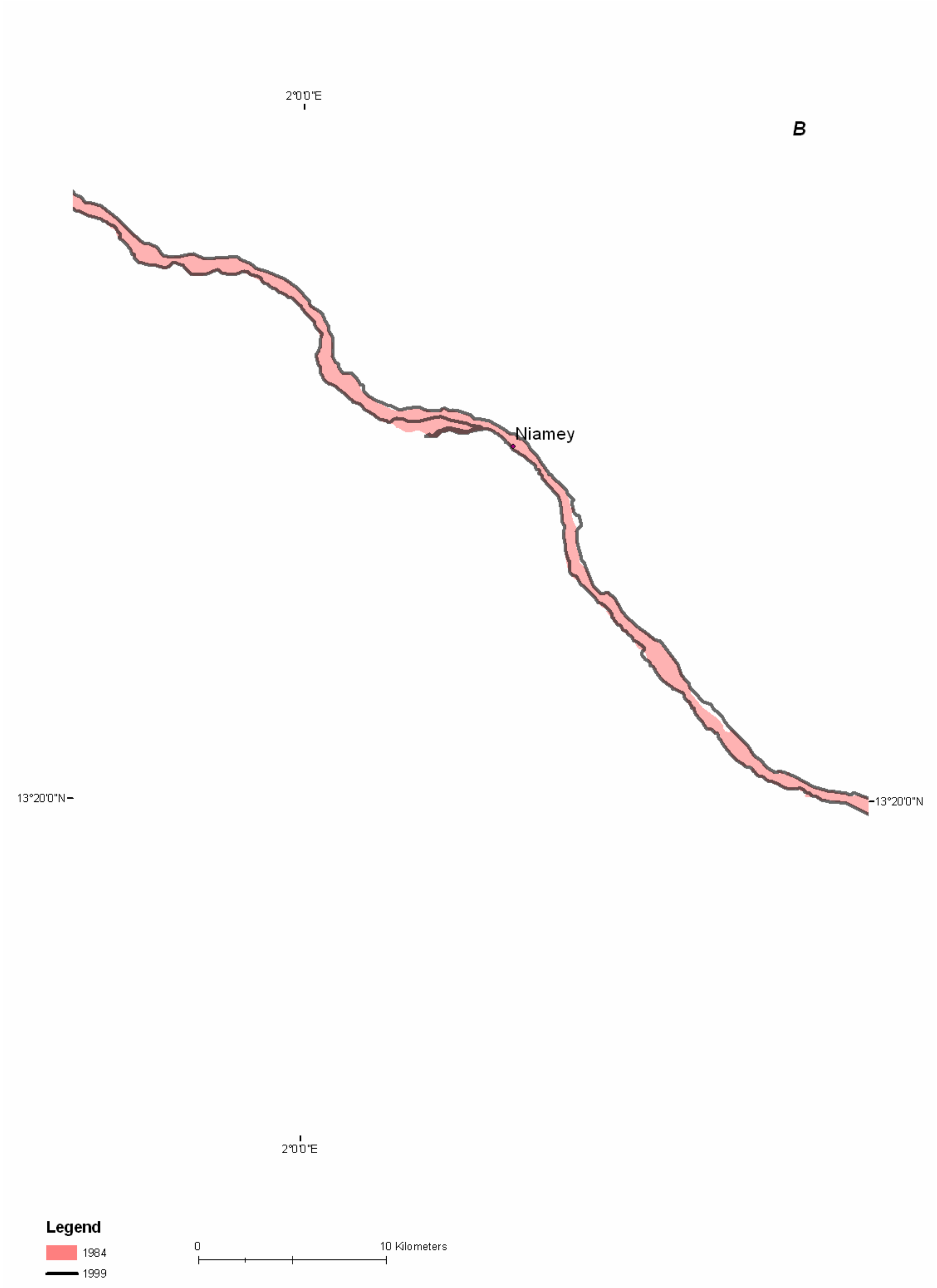


Figure B- 38B: Channel change in Reach 2 (1984-1999)

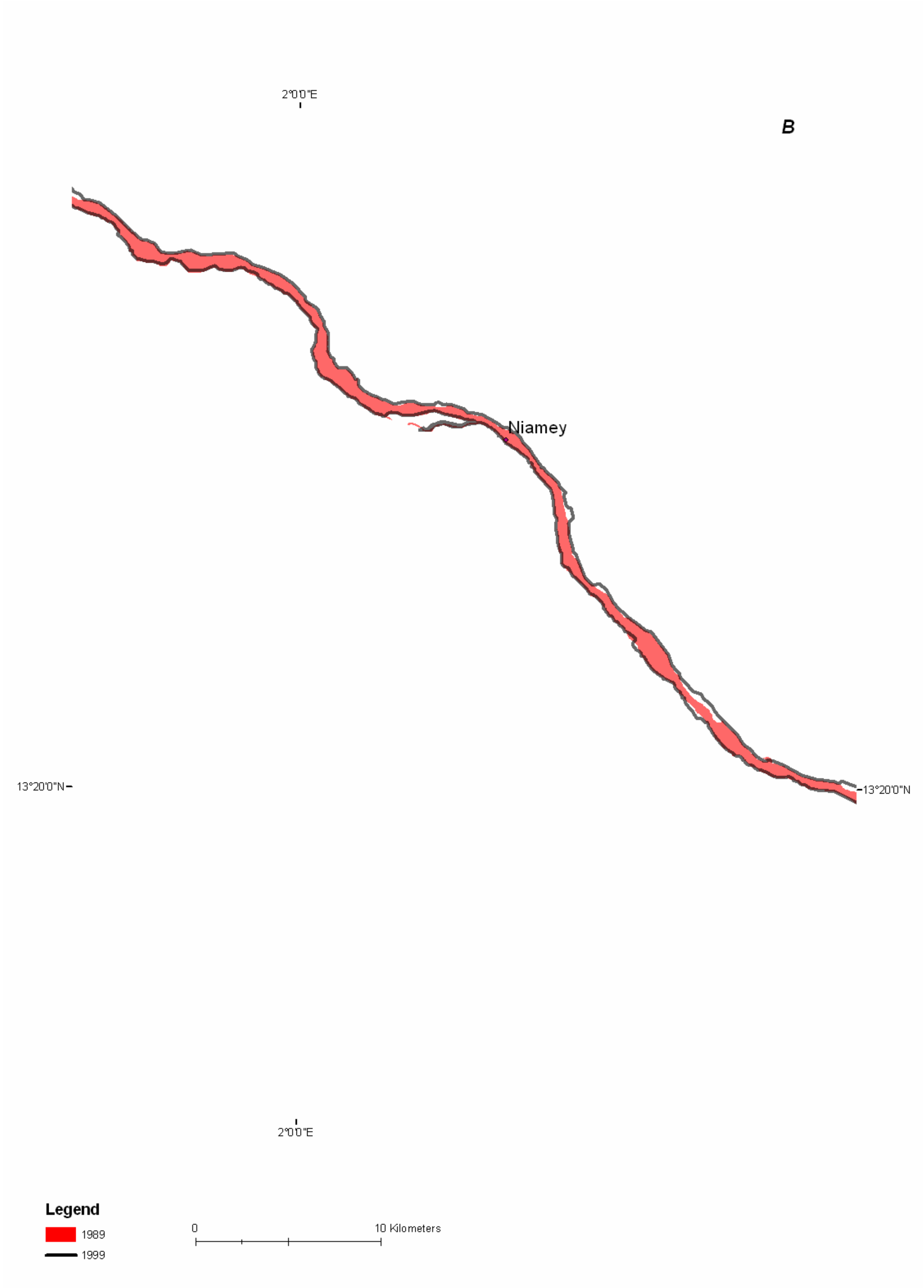


Figure B- 39B: Channel change in Reach 2 (1989-1999)

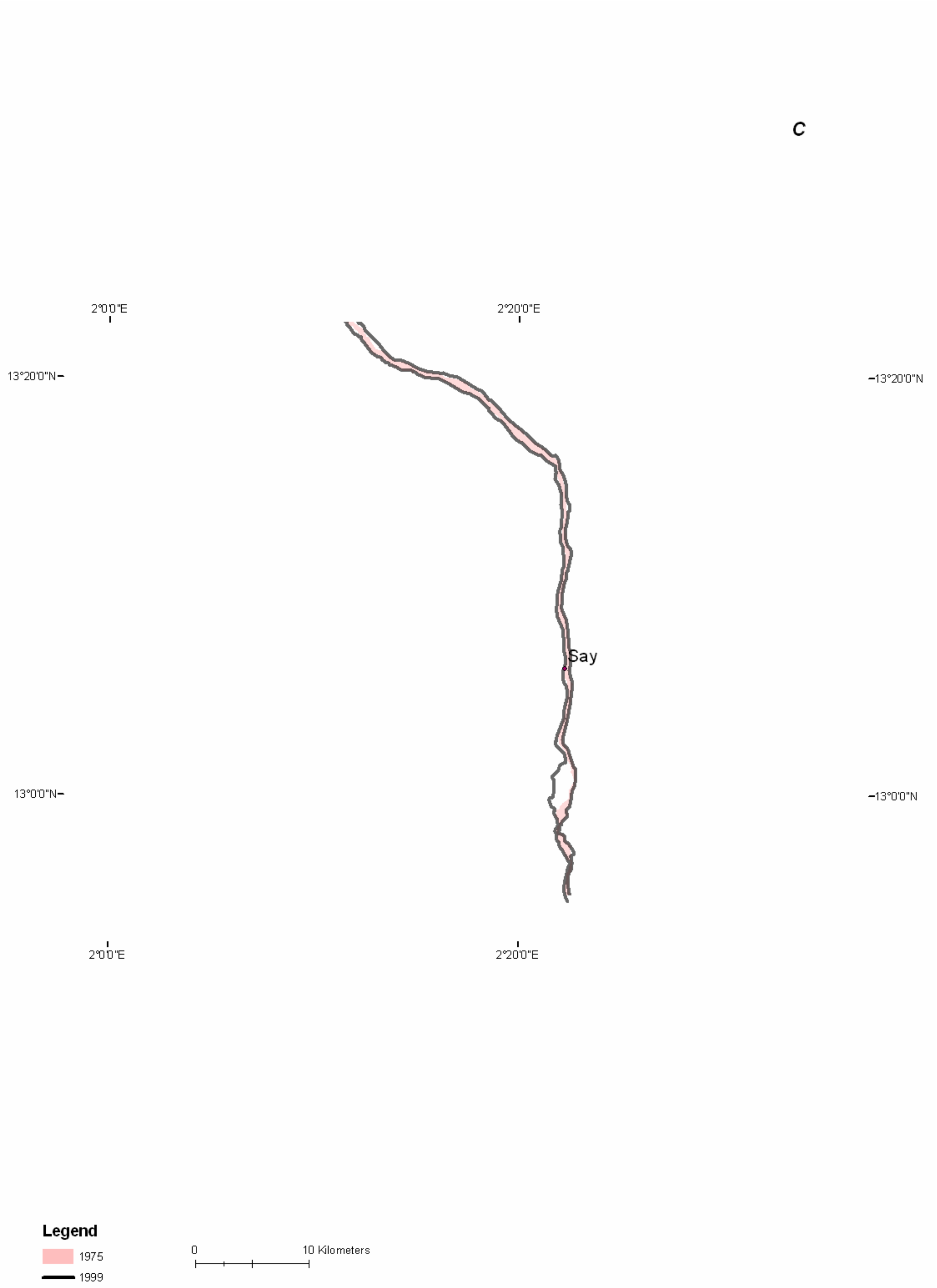


Figure B- 40C: Channel change in Reach 2 (1975-1999)

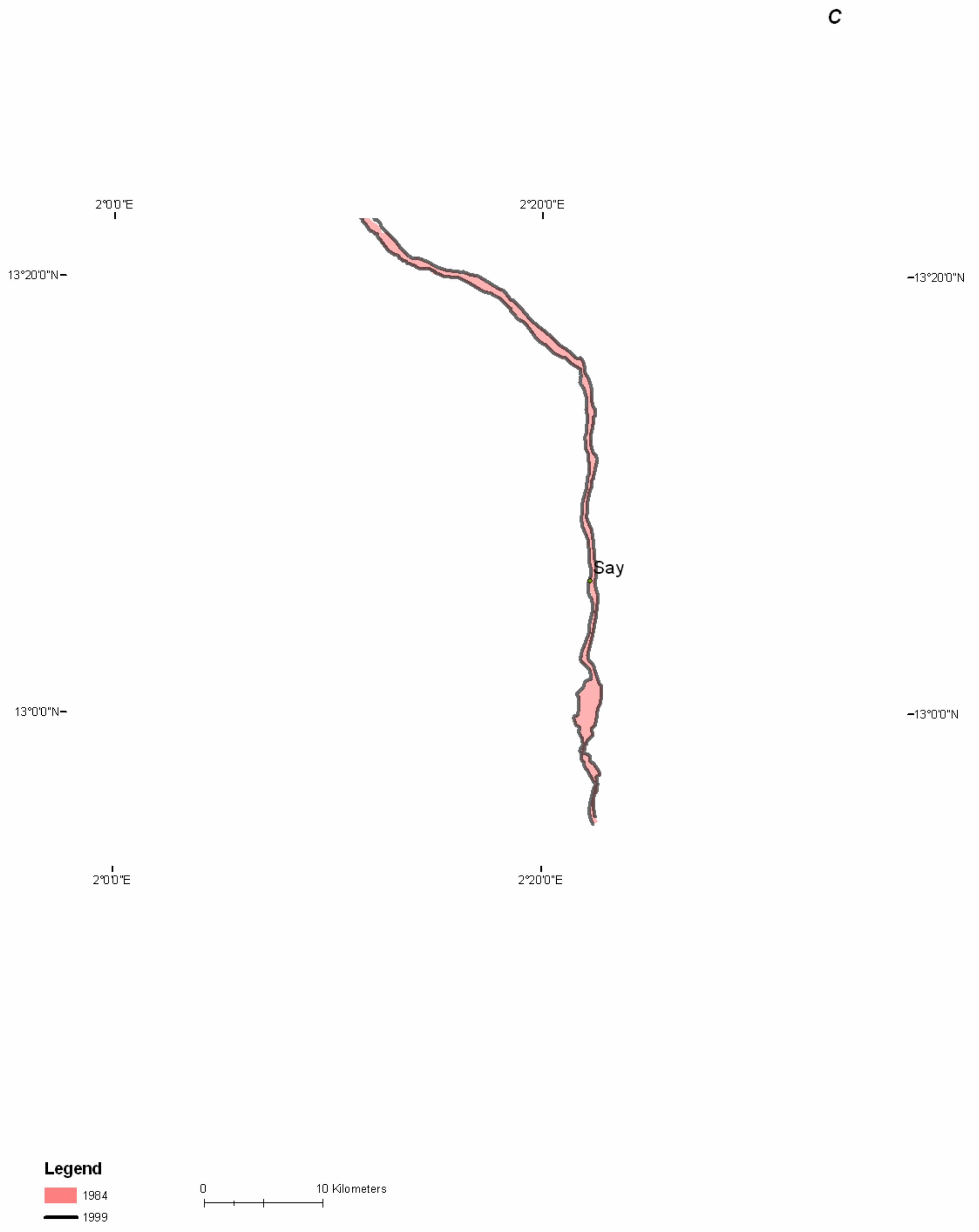


Figure B- 41C: Channel change in Reach 2 (1984-1999)

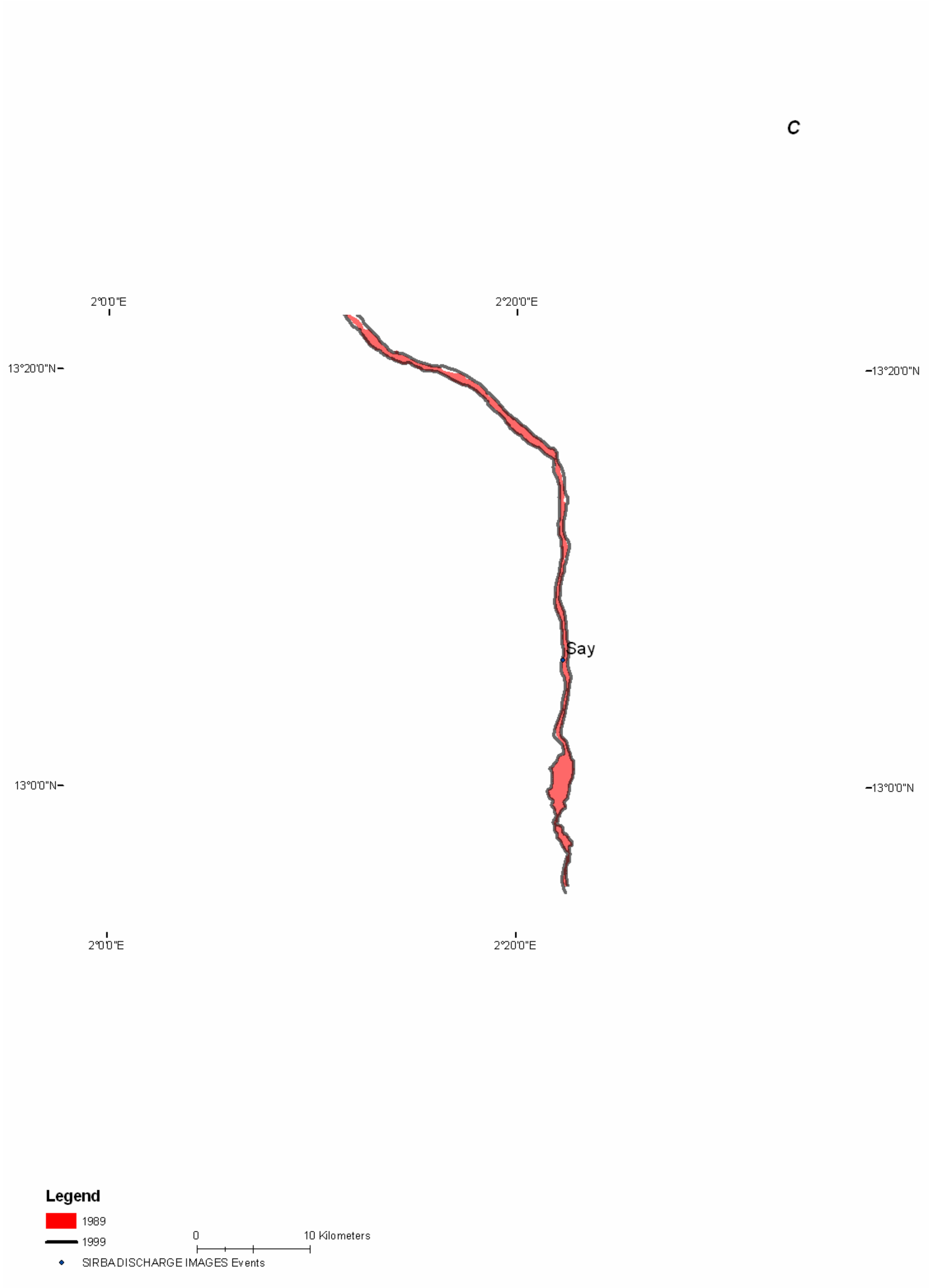


Figure B- 42C: Channel change in Reach 2 (1989-1999)

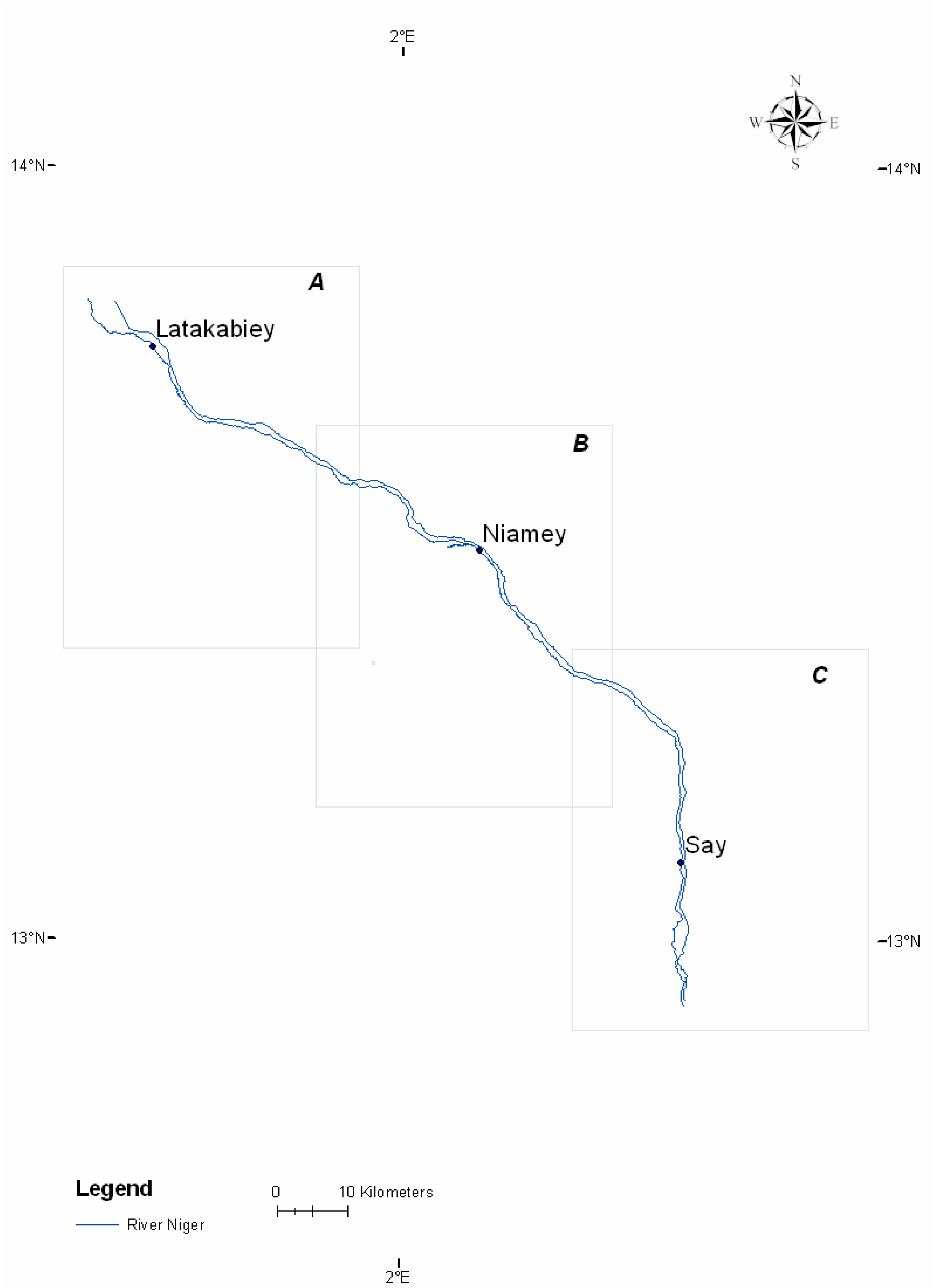


Figure B- 43 : Reach 2

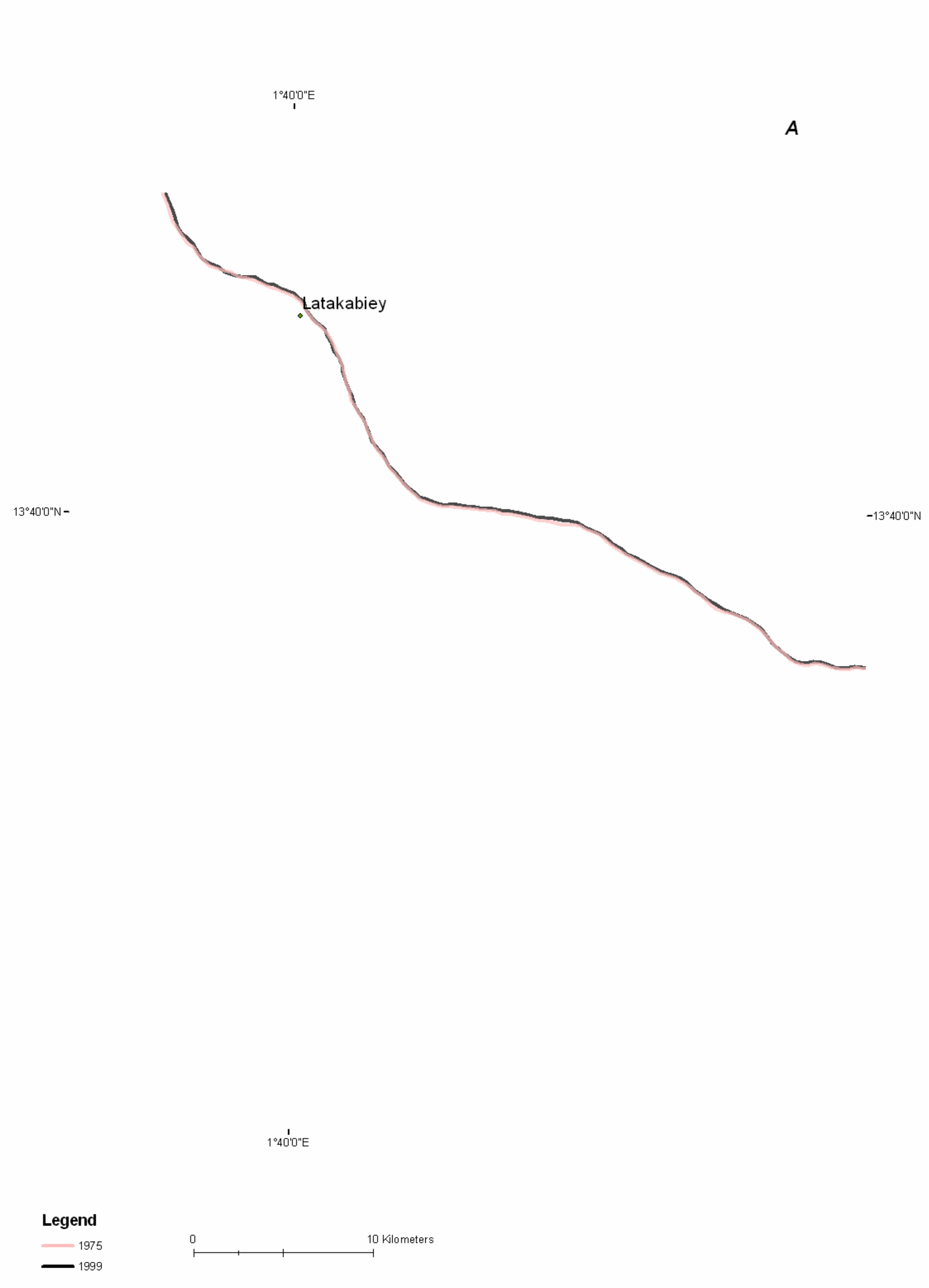


Figure B- 44A: River centre line change in reach 2 (1975 – 1999)

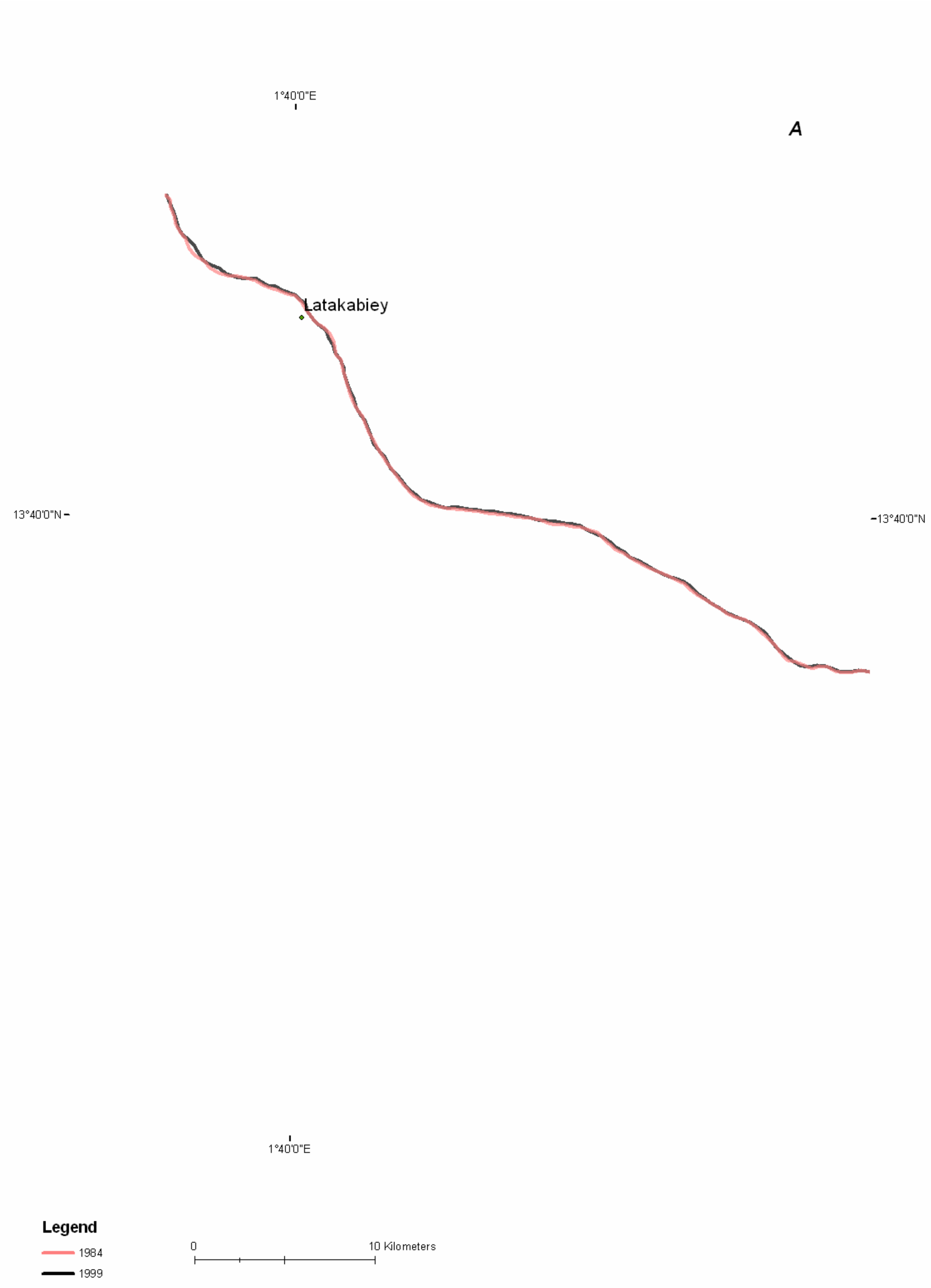


Figure B- 45A: River centre line change in reach 2 (1984 – 1999)

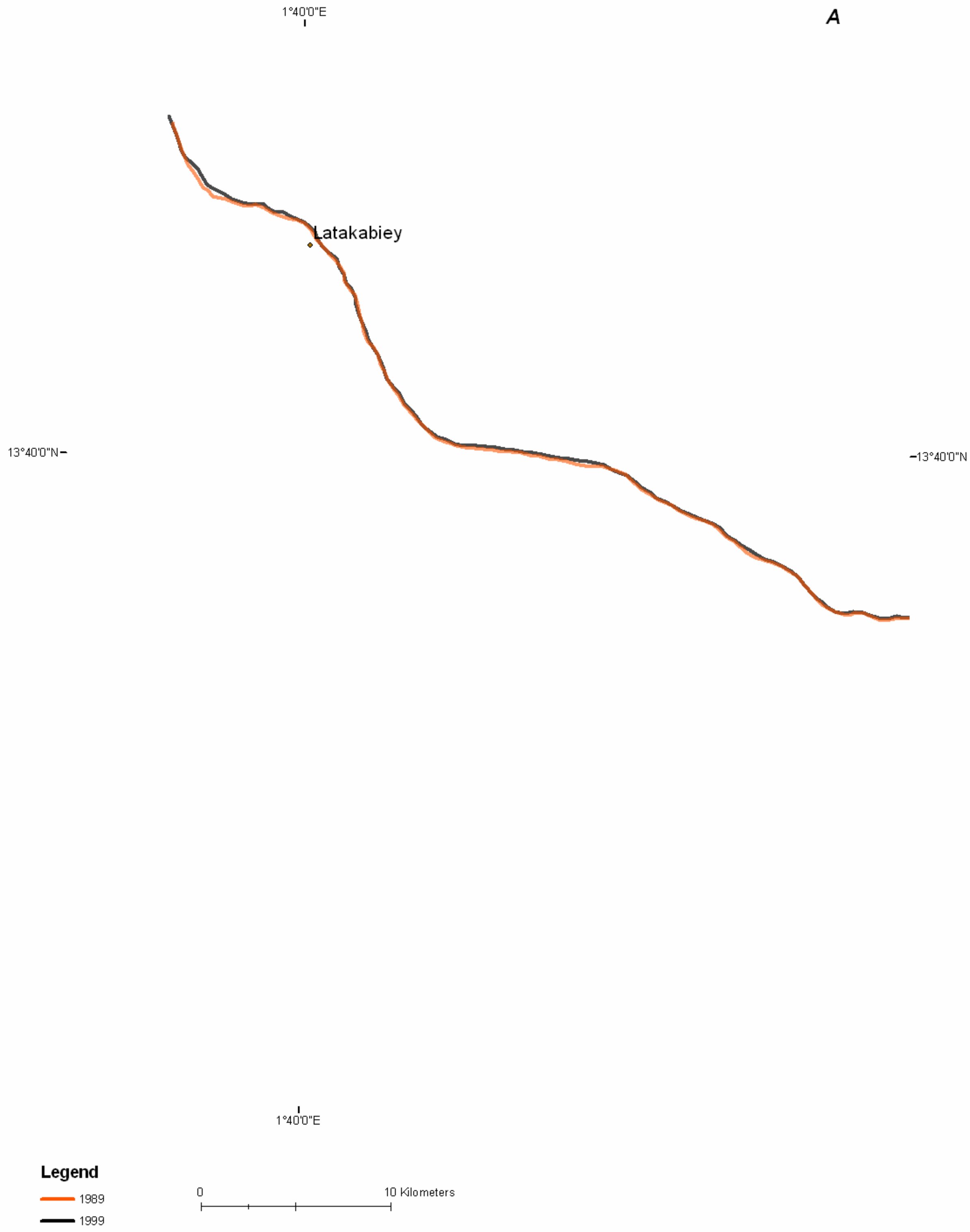


Figure B- 46A: River centre line change in reach 2 (1989 – 1999)

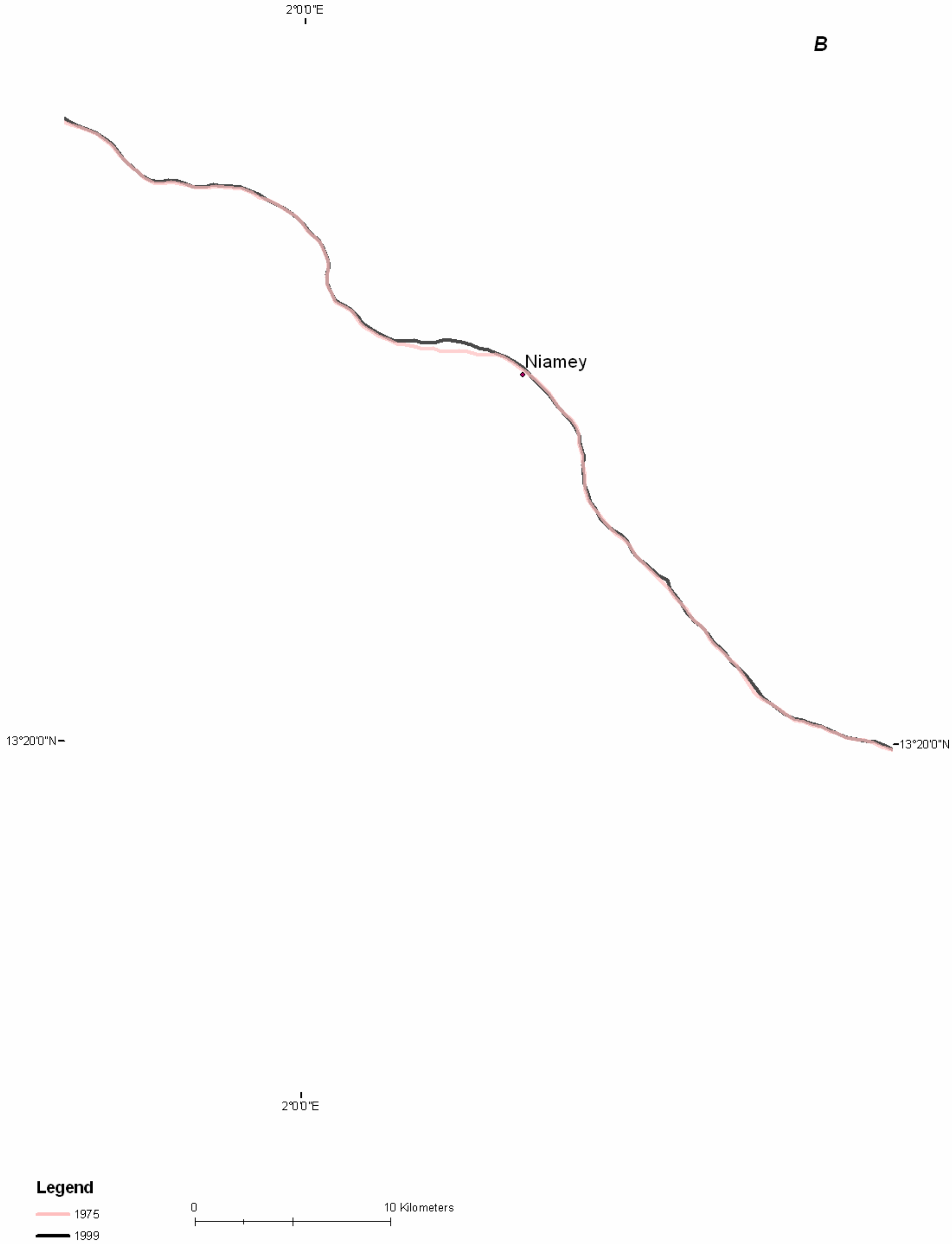


Figure B- 47B: River centre line change in reach 2 (1975 – 1999)

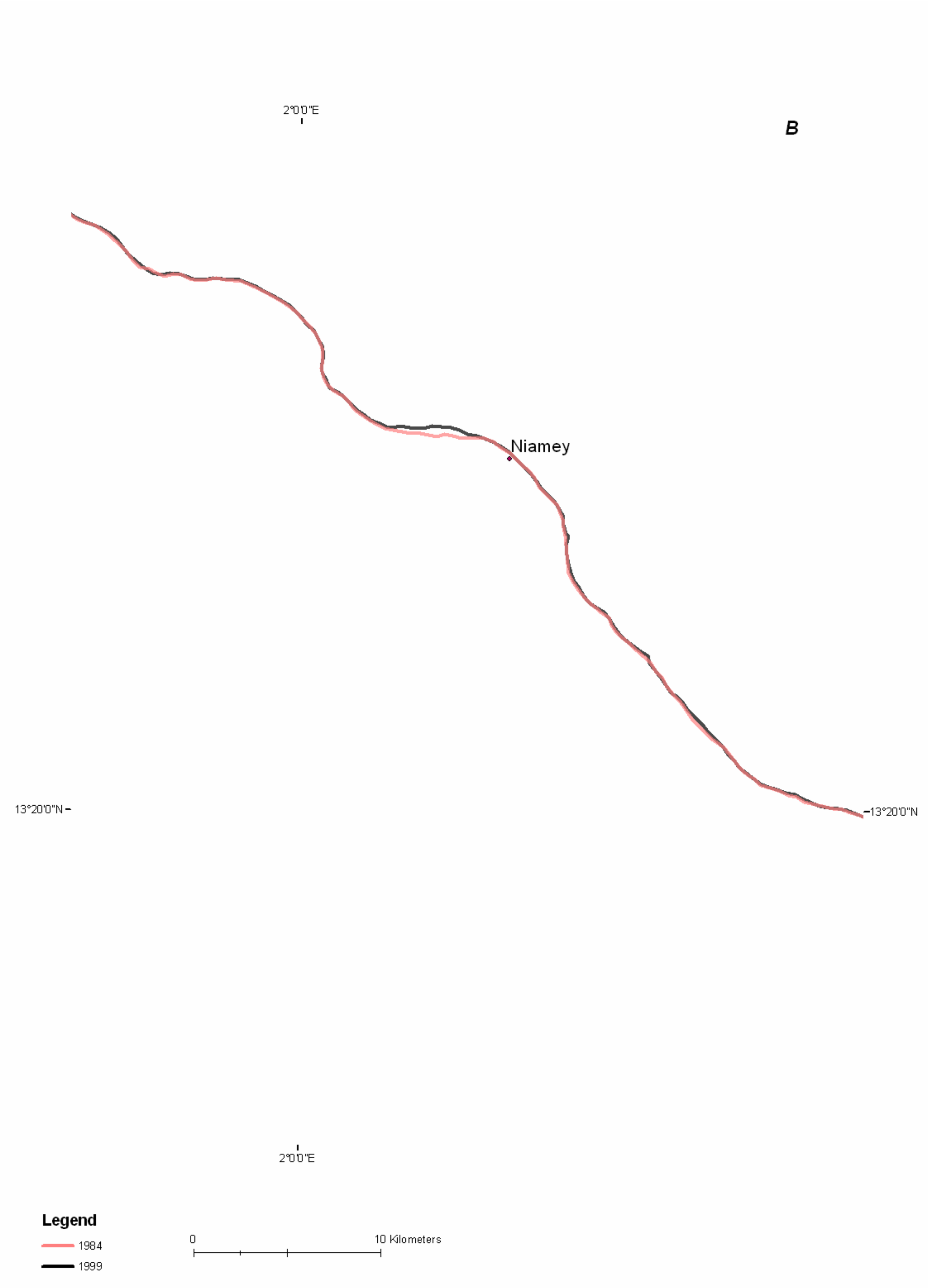


Figure B- 48B: River centre line change in reach 2 (1984 – 1999)

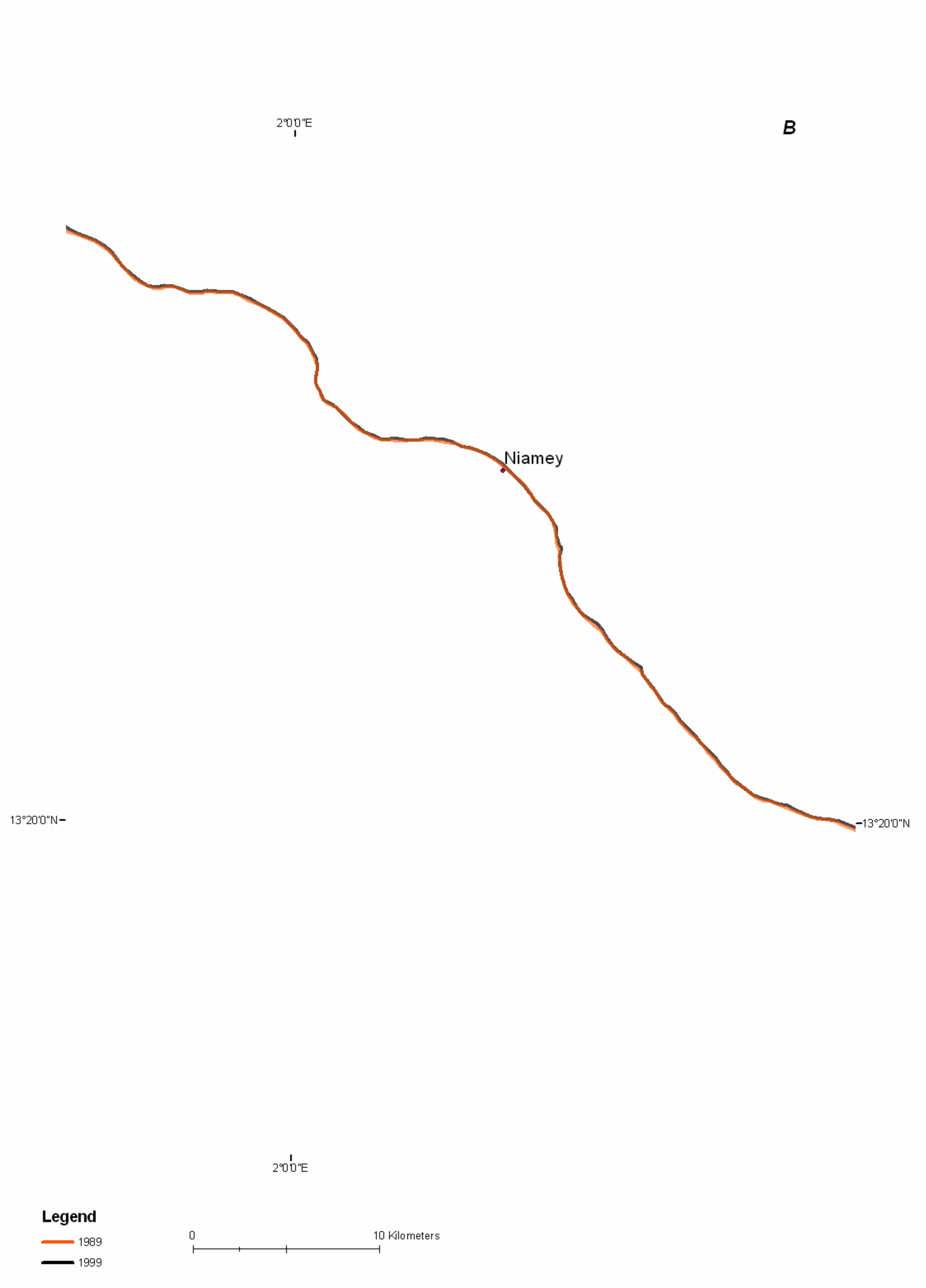


Figure B- 49B: River centre line change in reach 2 (1989 – 1999)

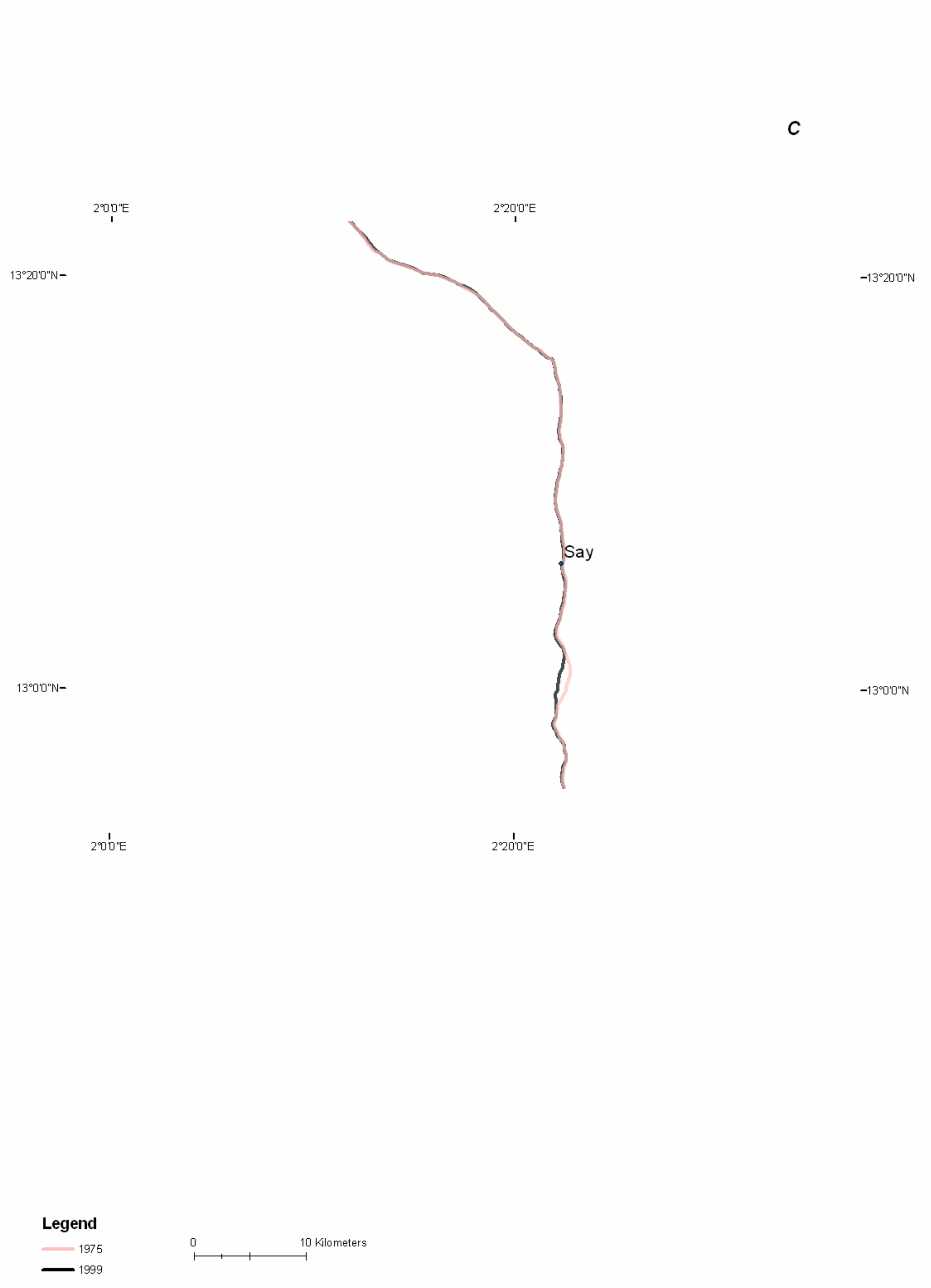


Figure B- 50C: River centre line change in reach 2 (1975 – 1999)

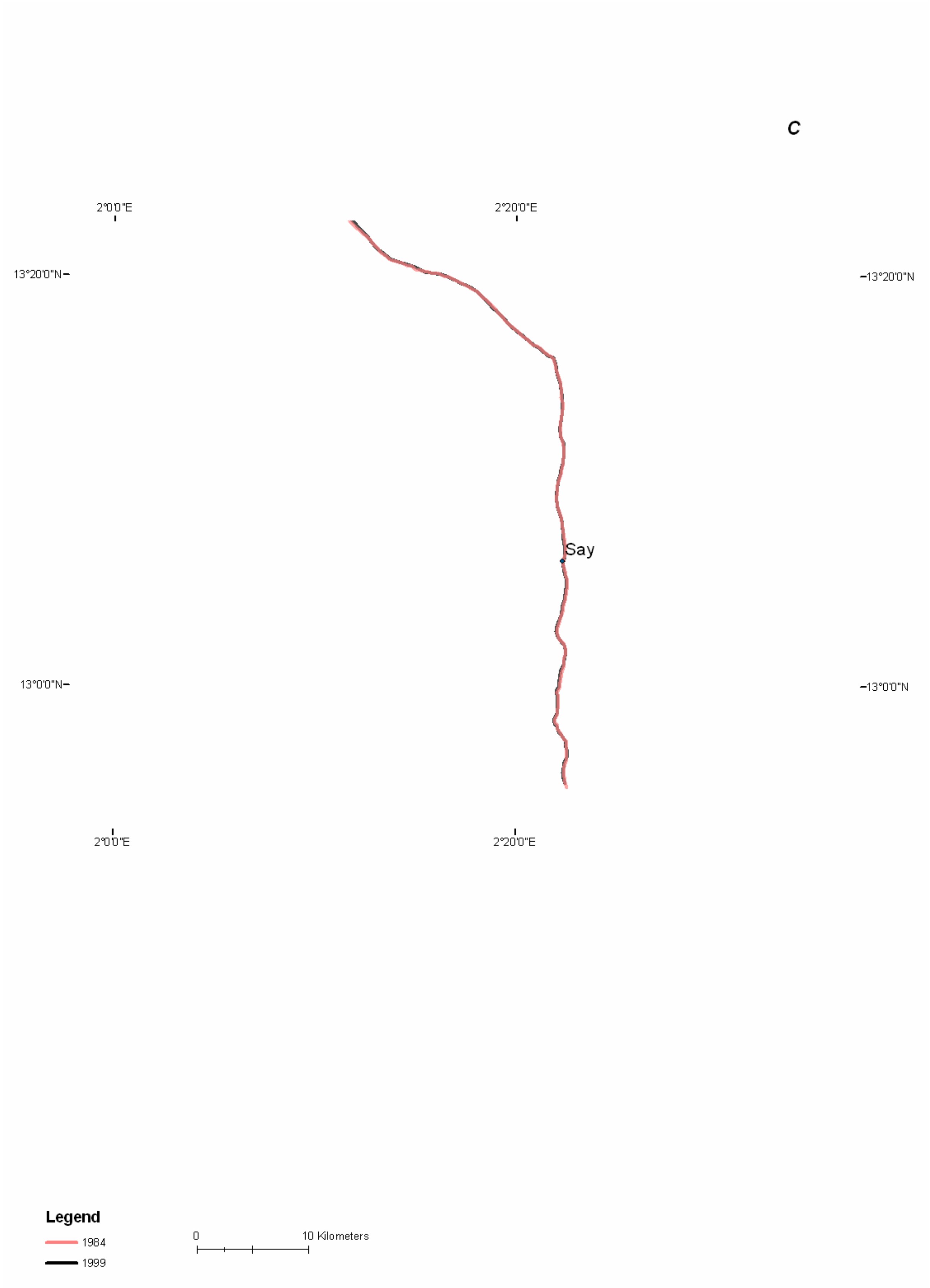


Figure B- 51C: River centre line change in reach 2 (1984 – 1999)

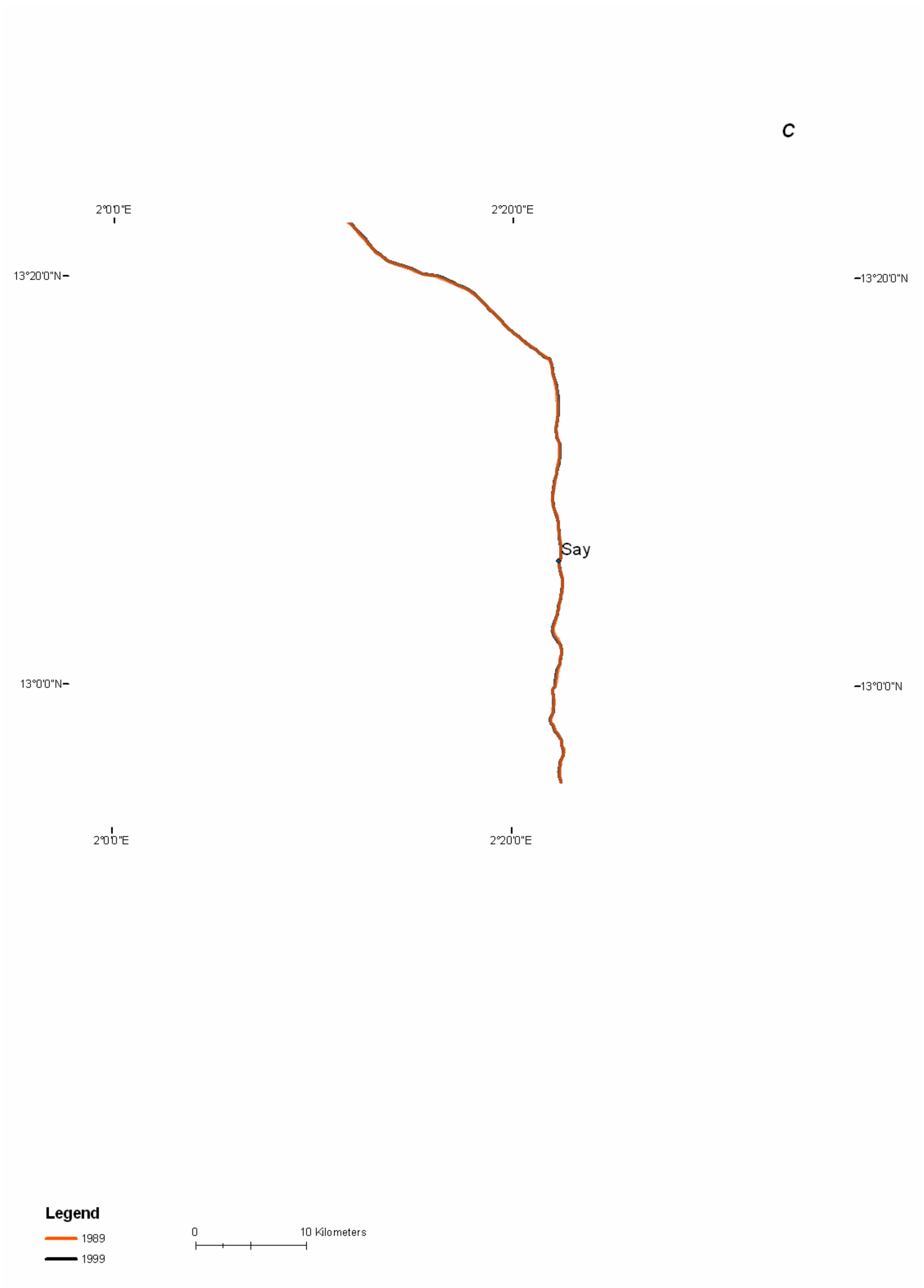


Figure B- 52C: River centre line change in reach 2 (1989 – 1999)

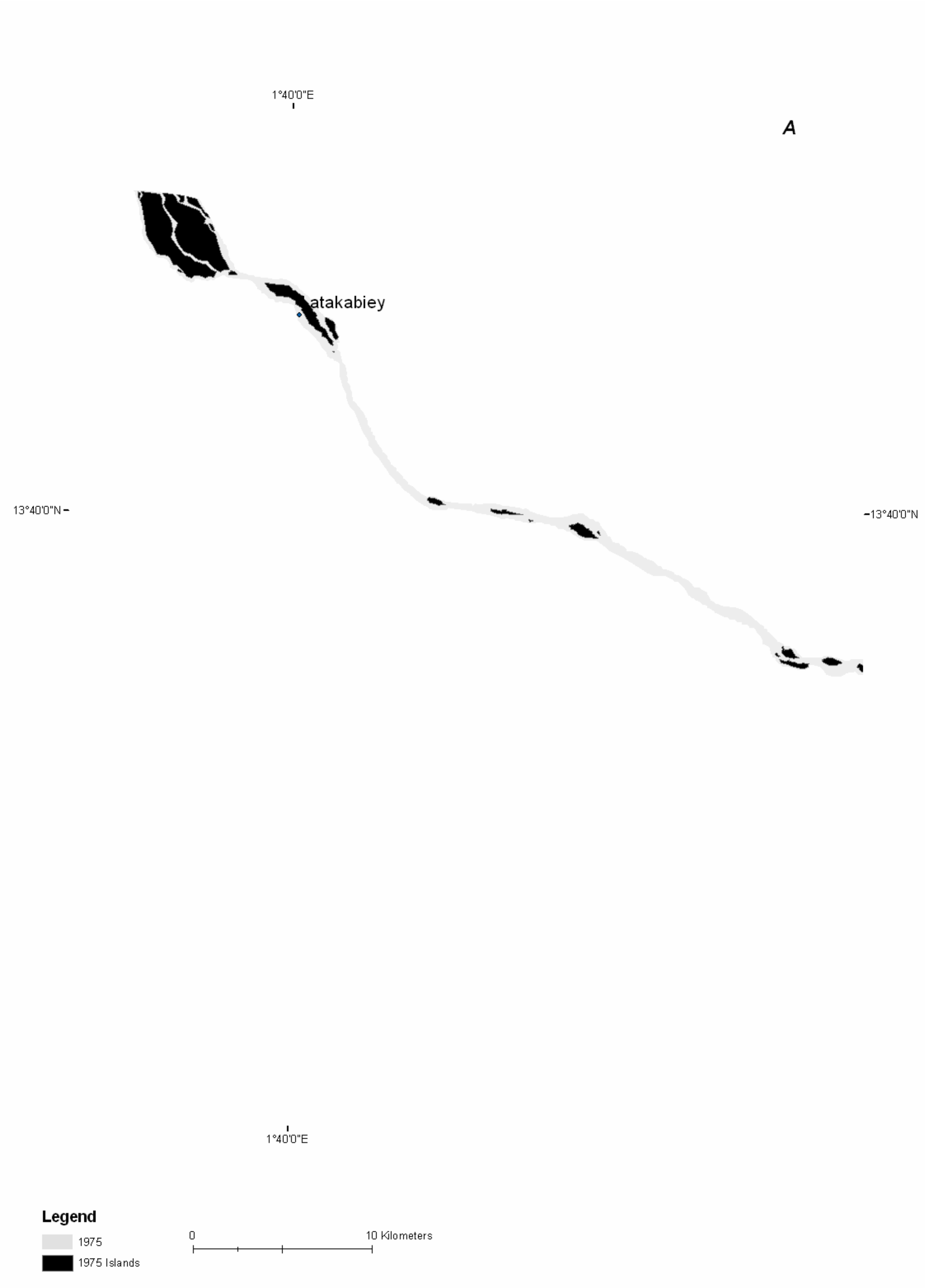


Figure B- 53A: Reach 2 channel bank and island extents in 1975

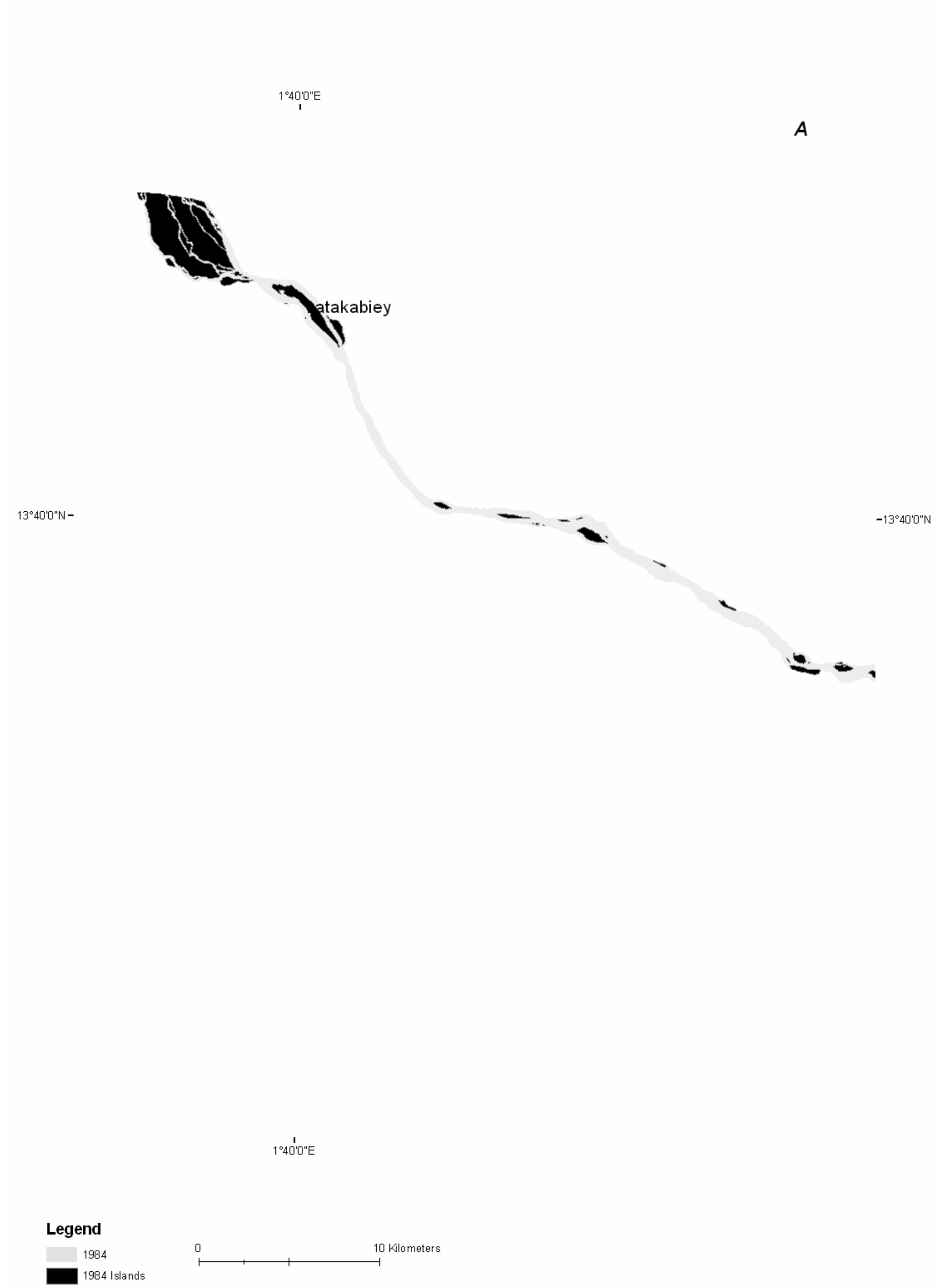


Figure B- 54A: Reach 2 channel bank and island extents in 1984

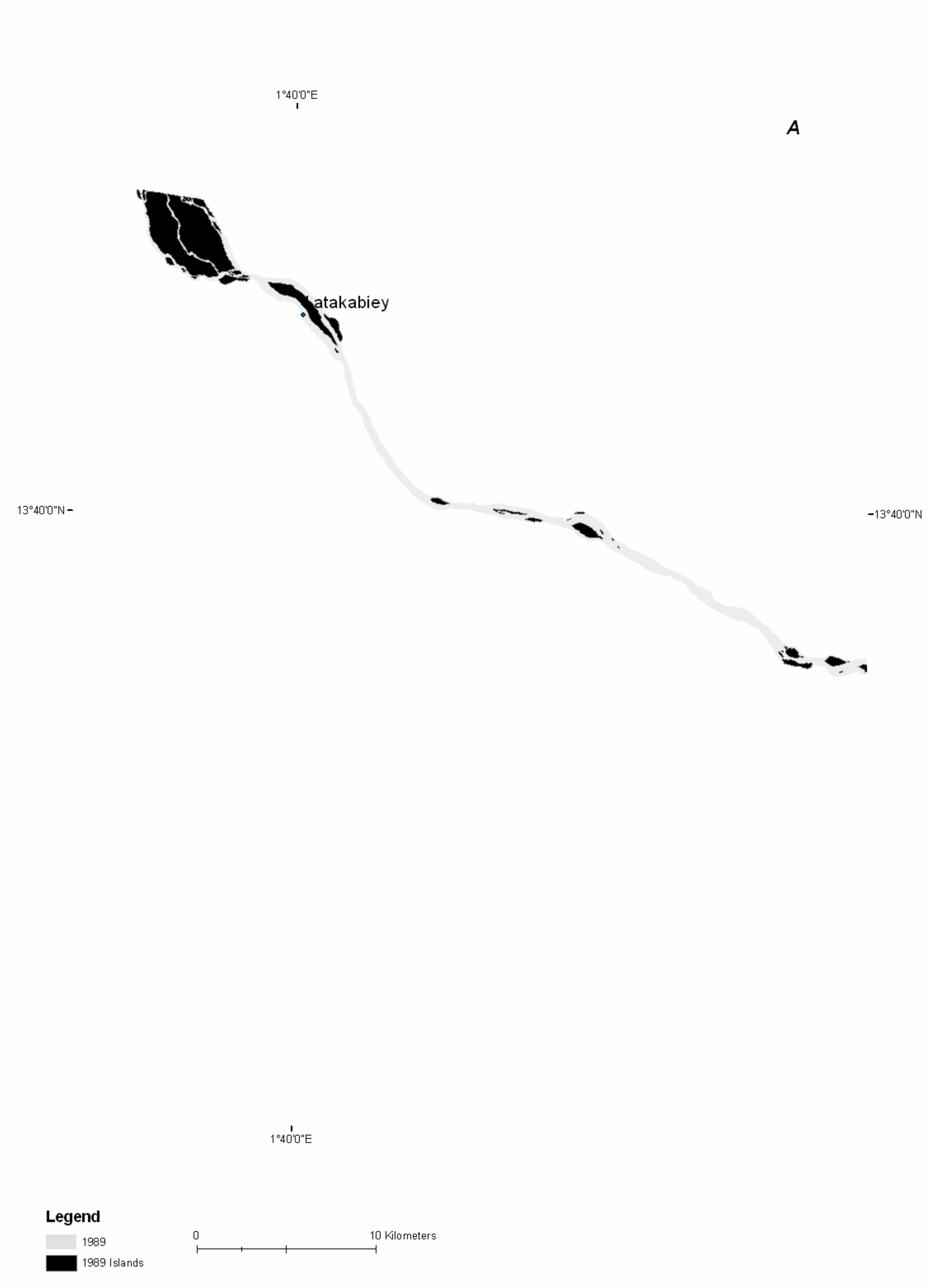


Figure B- 55A: Reach 2 channel bank and island extents in 1989

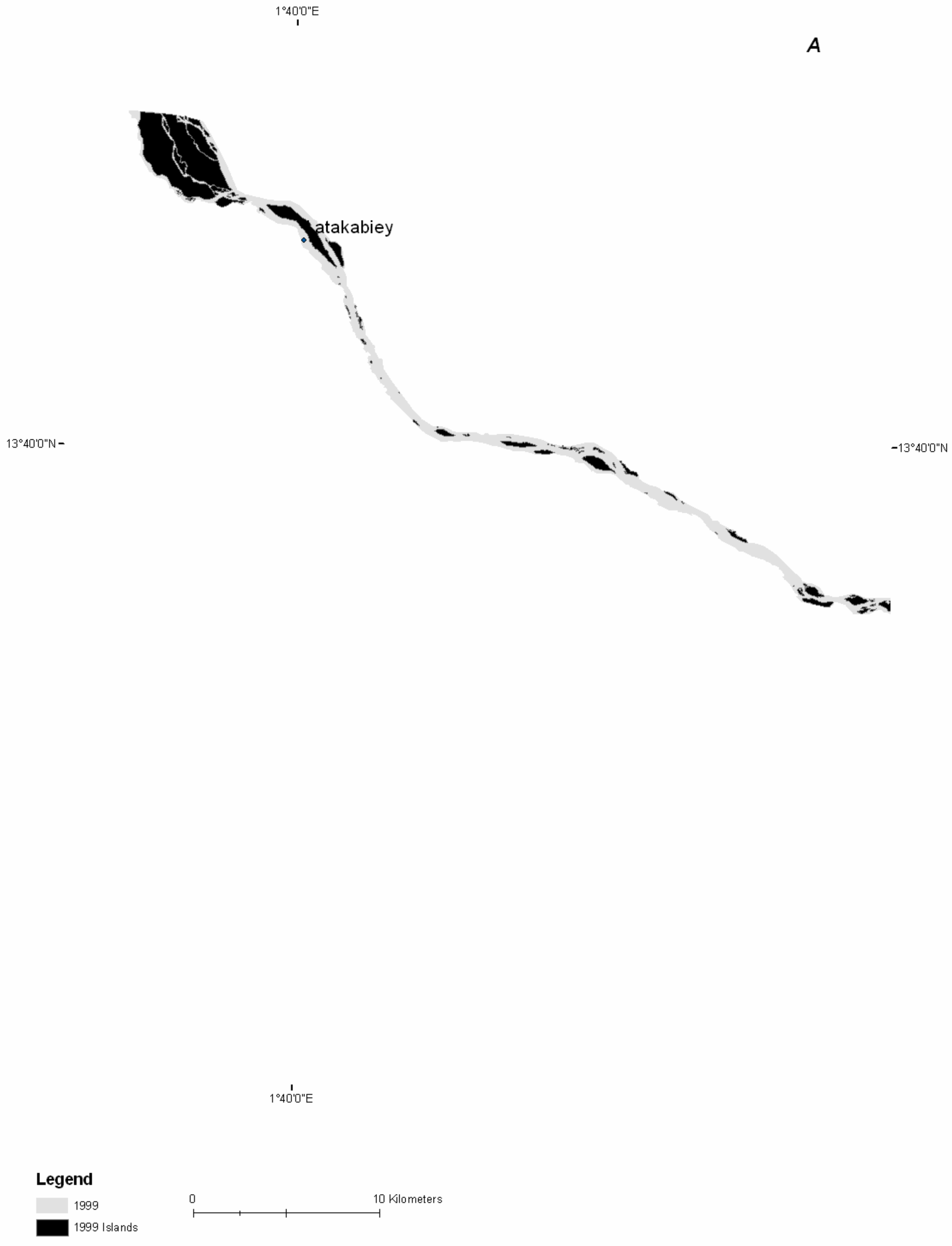


Figure B- 56A: Reach 2 channel bank and island extents in 1999

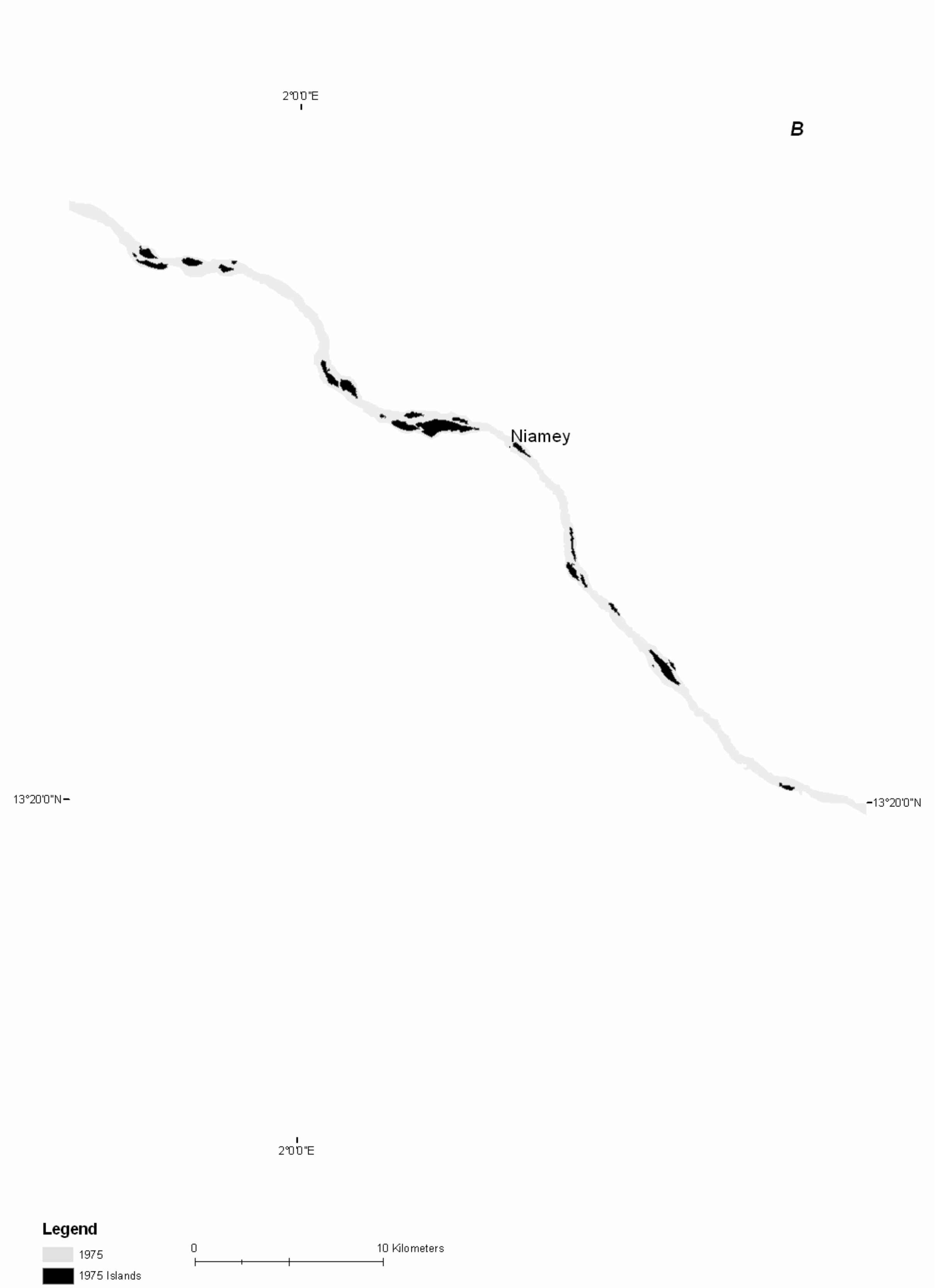


Figure B- 57B: Reach 2 channel bank and island extents in 1975

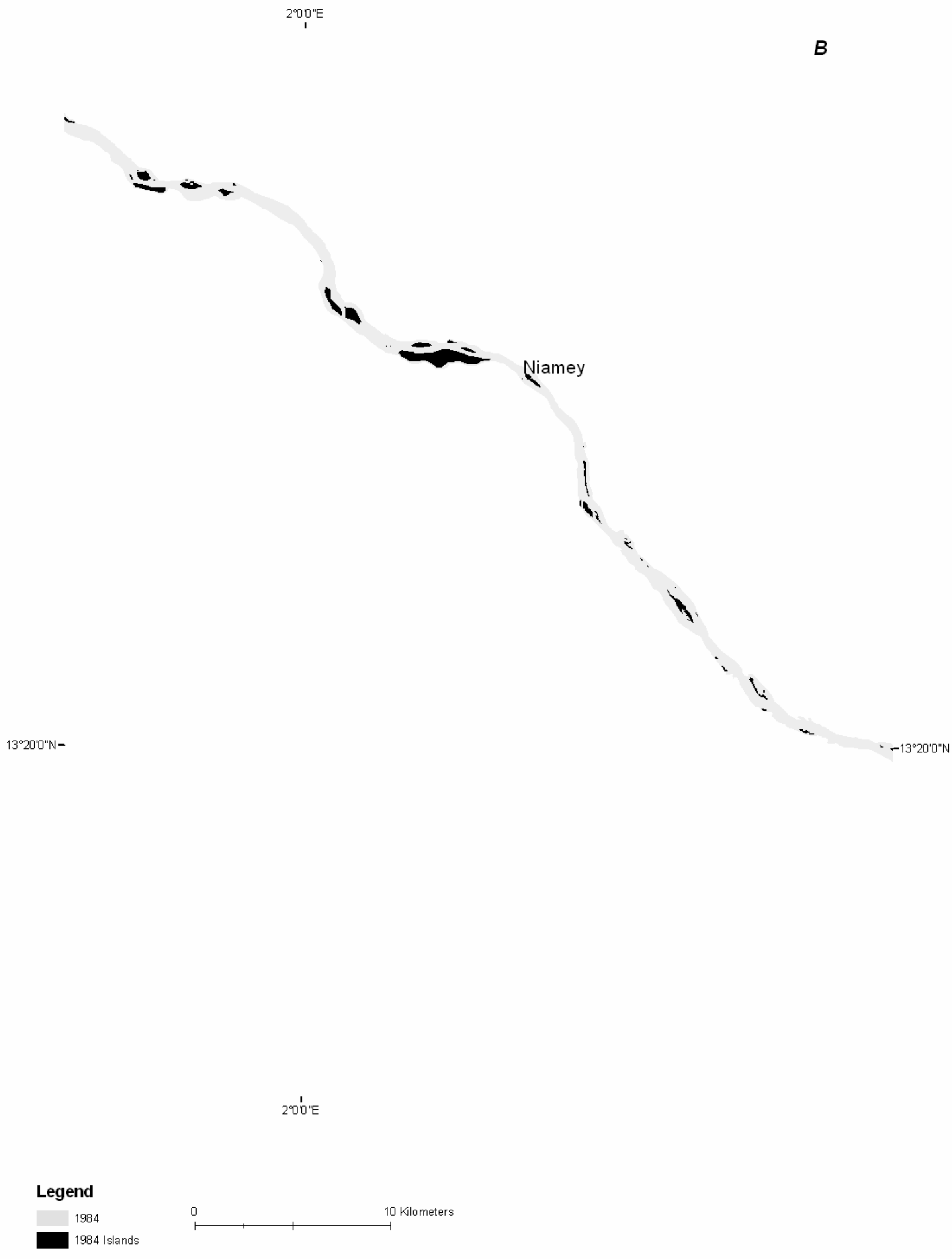


Figure B- 58B: Reach 2 channel bank and island extents in 1984

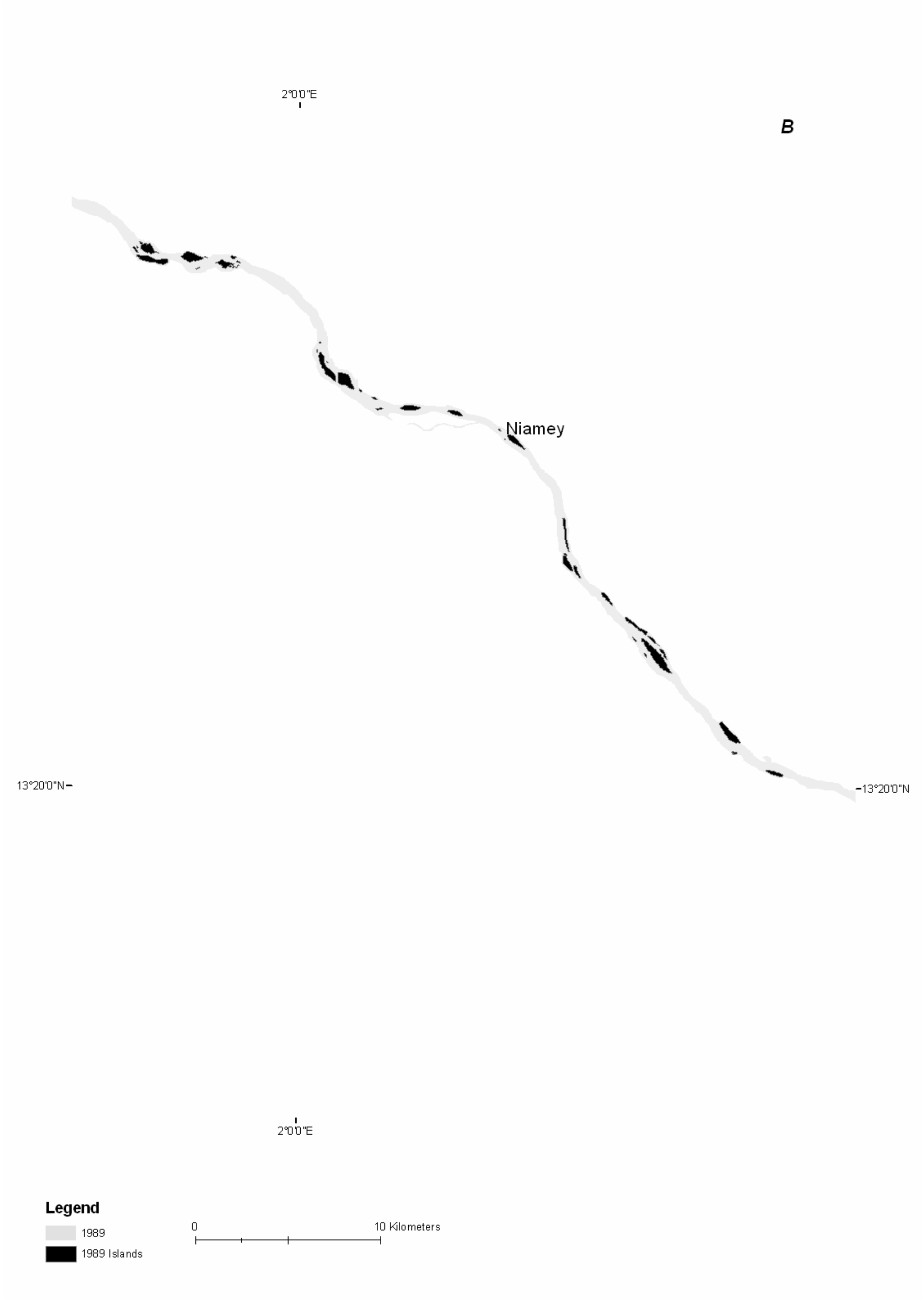


Figure B- 59B: Reach 2 channel bank and island extents in 1989

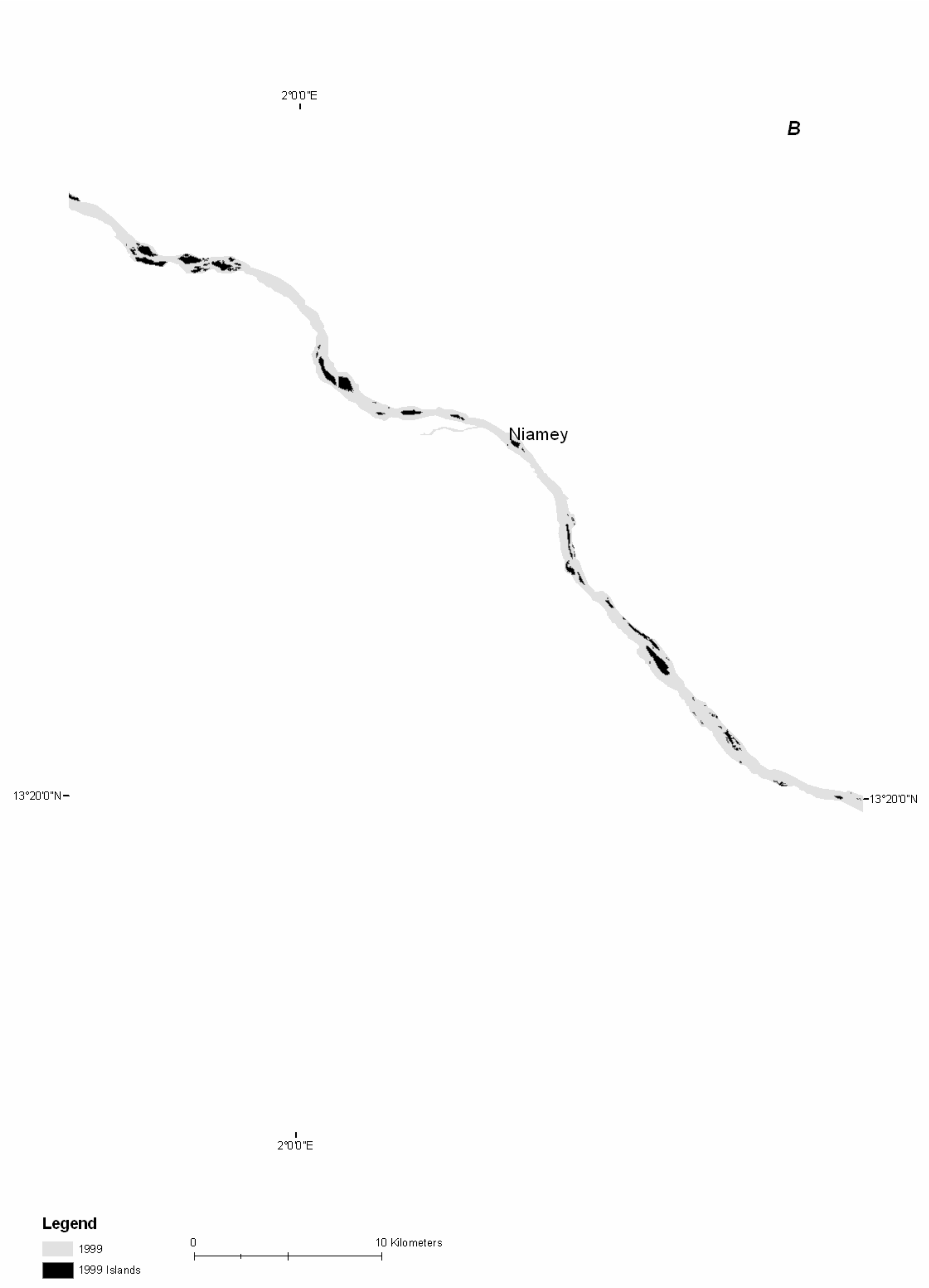


Figure B- 60B: Reach 2 channel bank and island extents in 1999

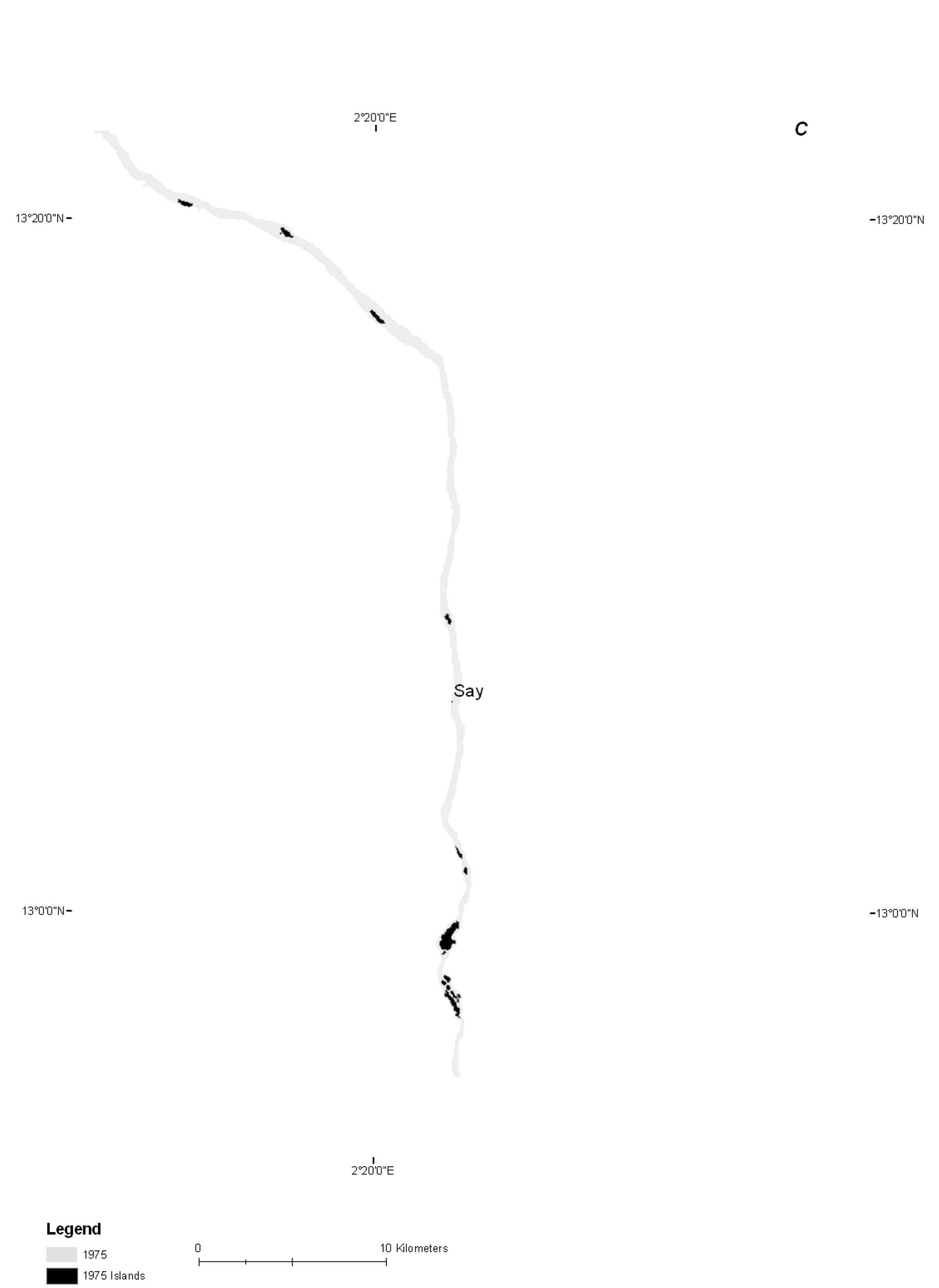


Figure B- 61C: Reach 2 channel bank and island extents in 1975

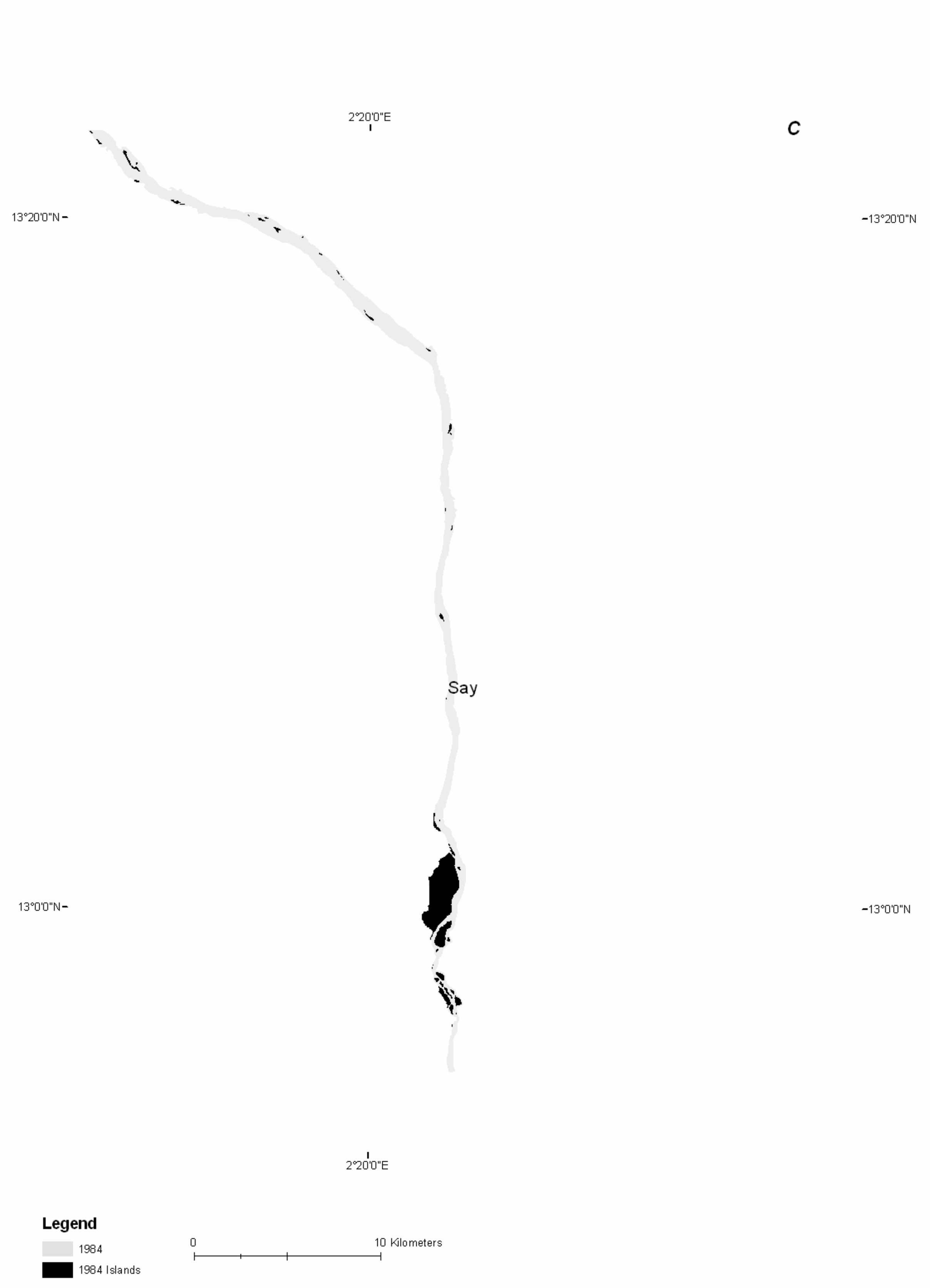


Figure B- 62C: Reach 2 channel bank and island extents in 1984

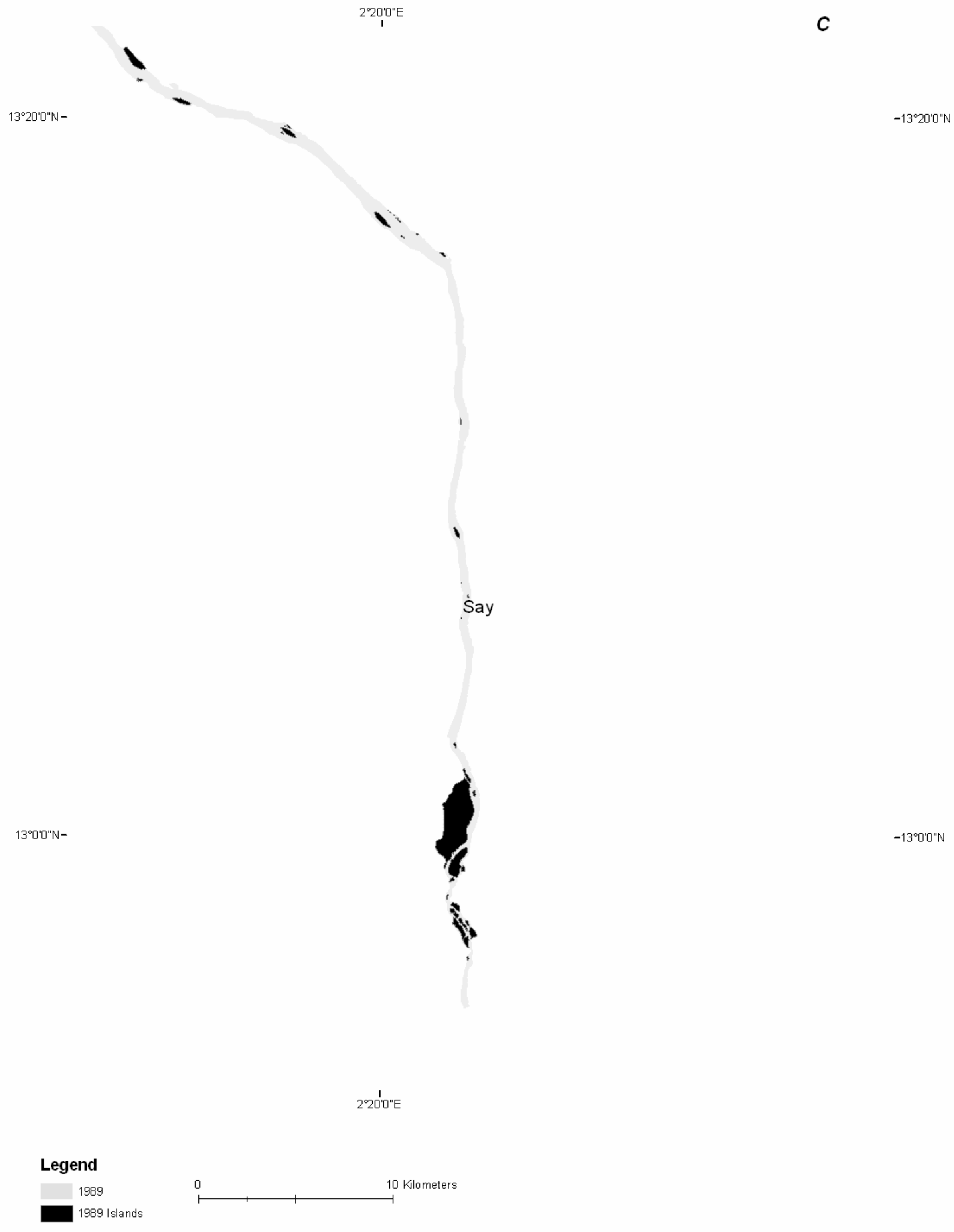


Figure B- 63C: Reach 2 channel bank and island extents in 1989

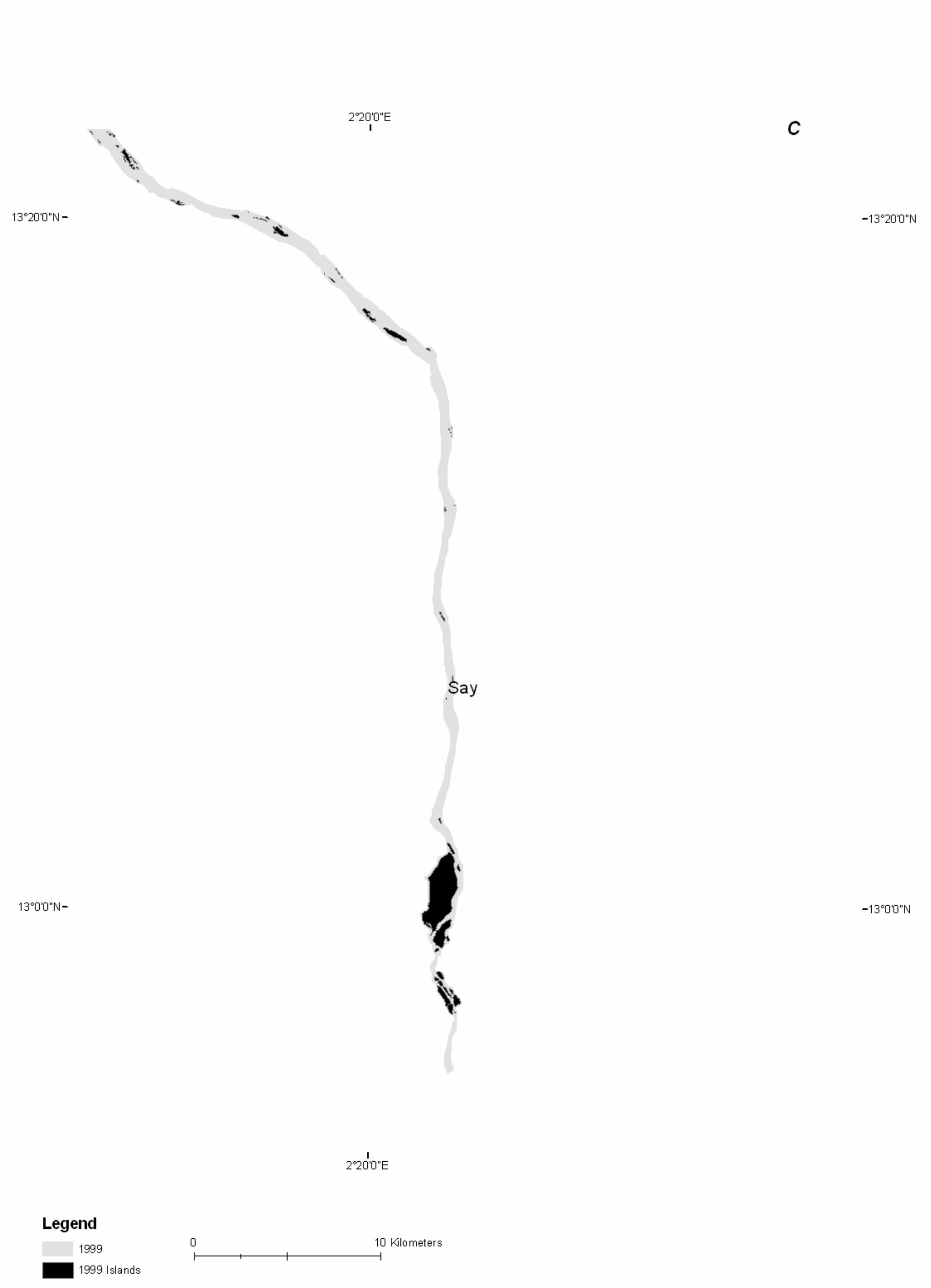


Figure B- 64C: Reach 2 channel bank and island extents in 1999

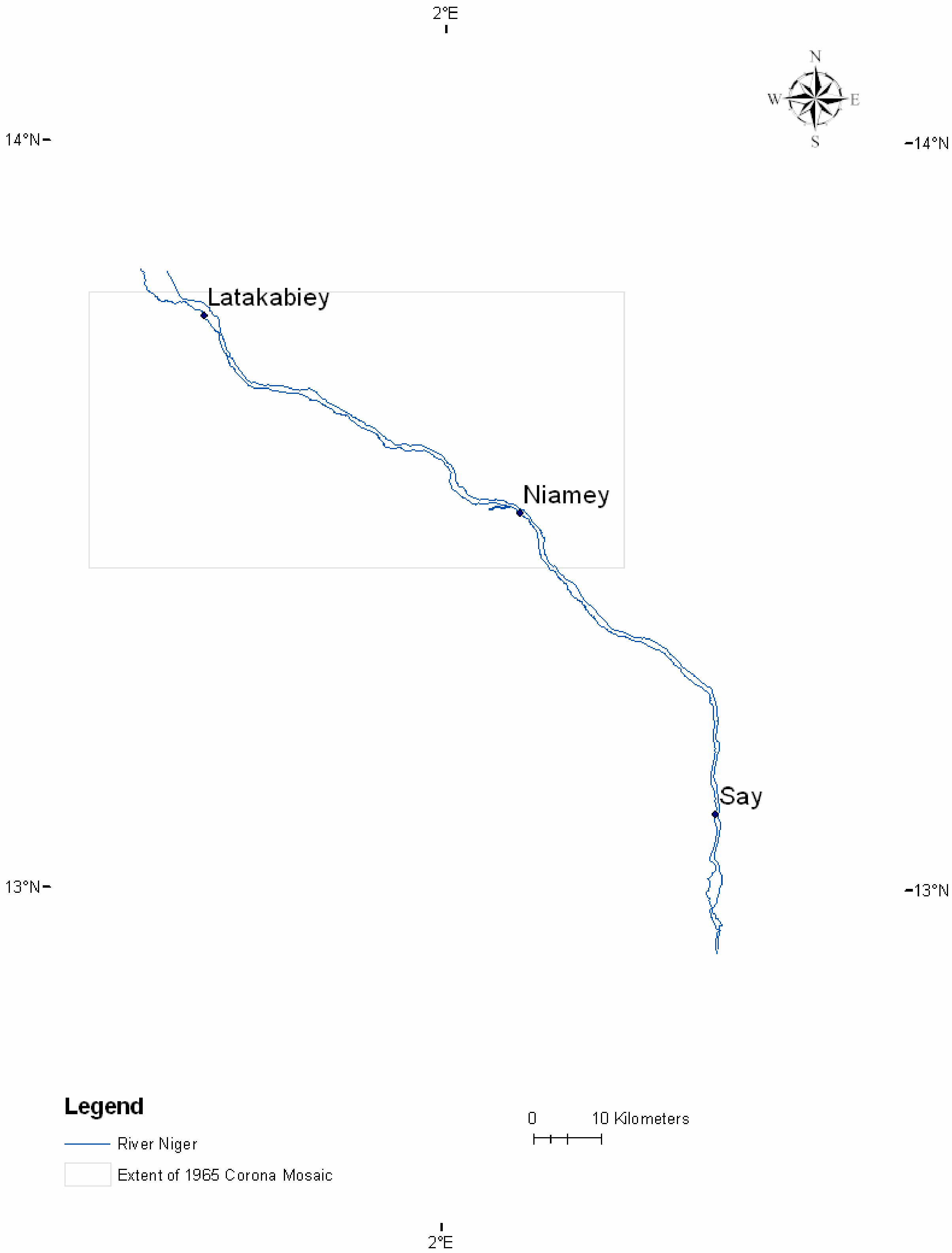


Figure B- 65: Position of the 1965 Corona imagery in reach 2

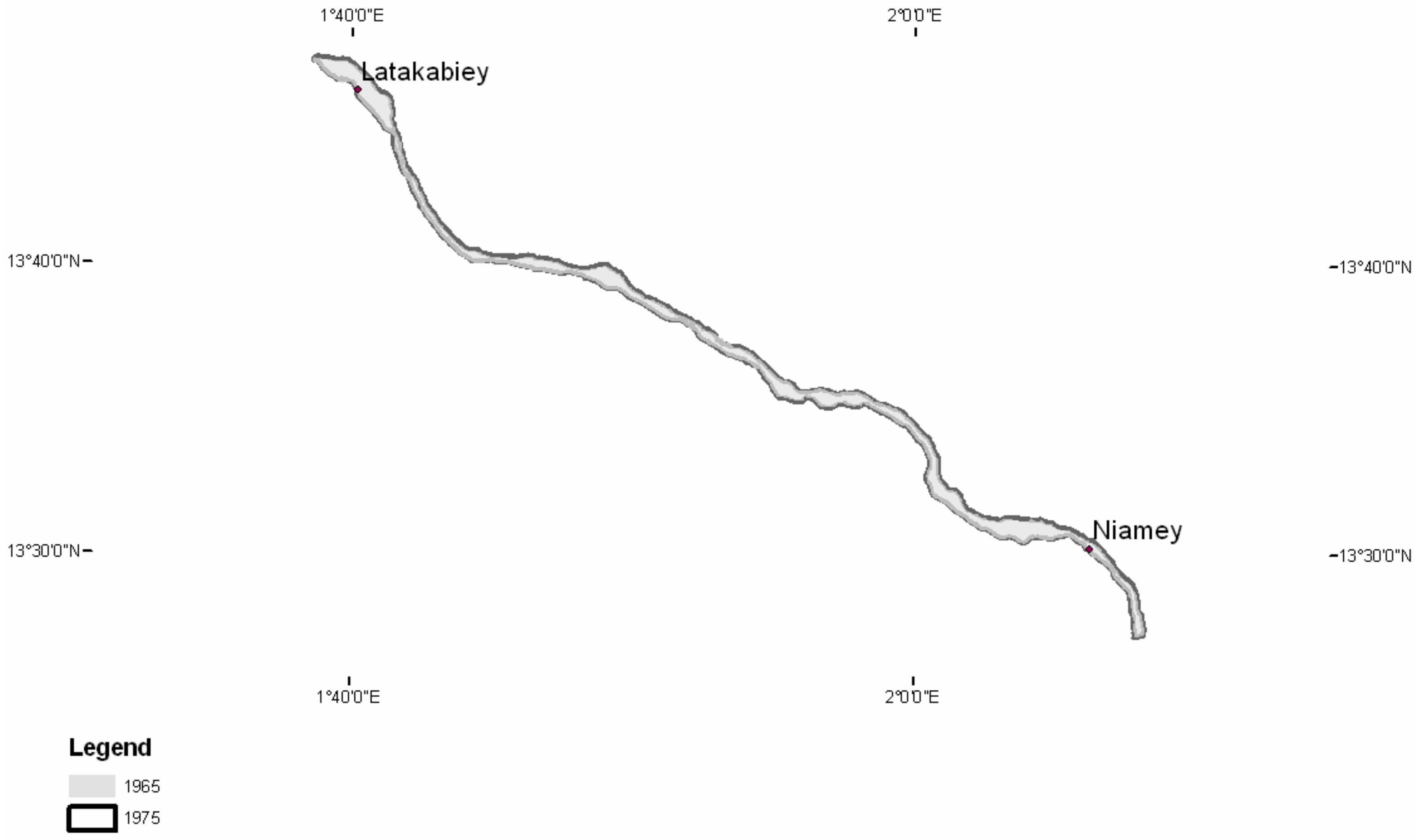


Figure B- 66: Channel change in a stretch of Reach 2 (1965-1975)

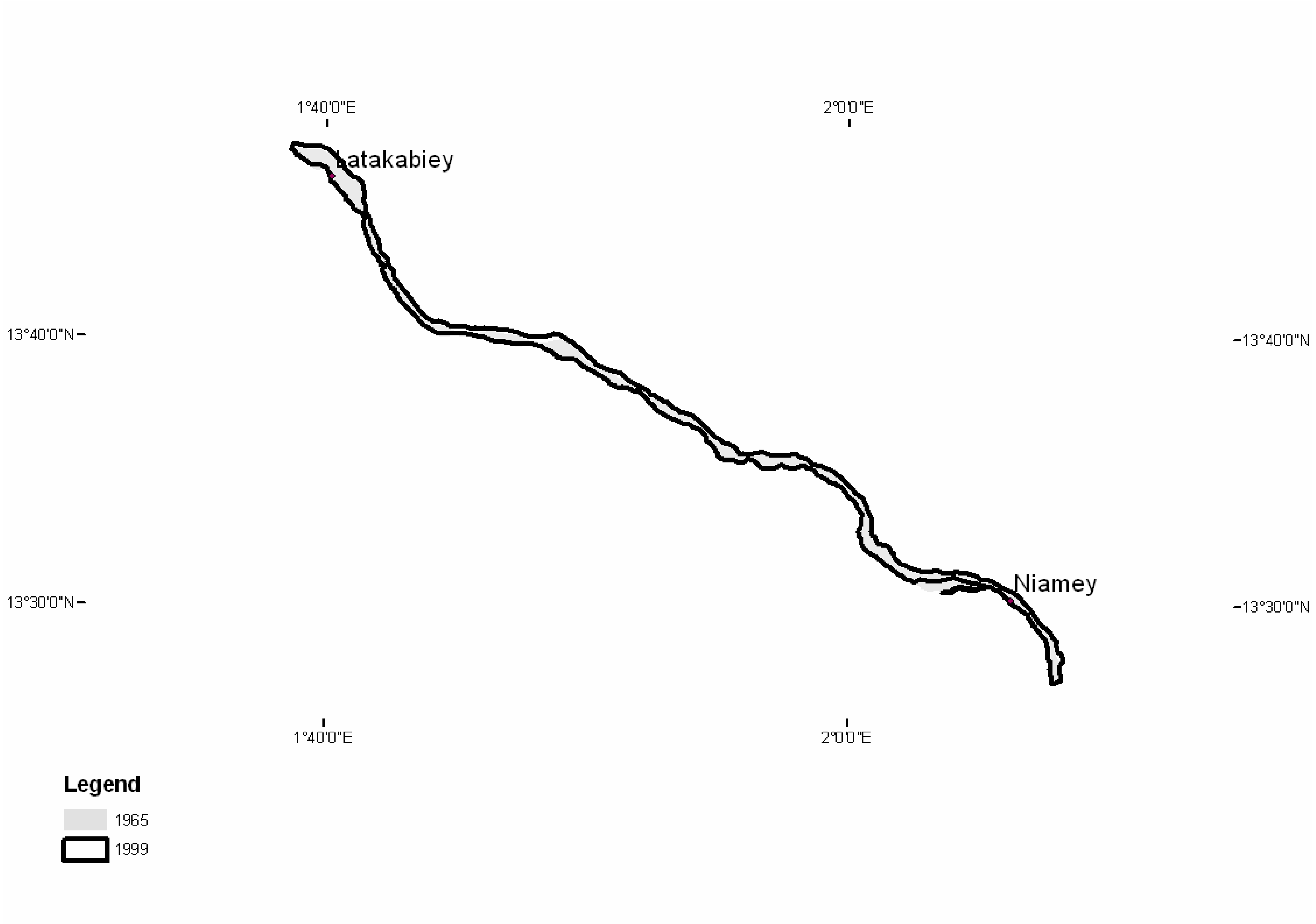


Figure B- 67: Channel change in a stretch of Reach 2 (1965-1999)

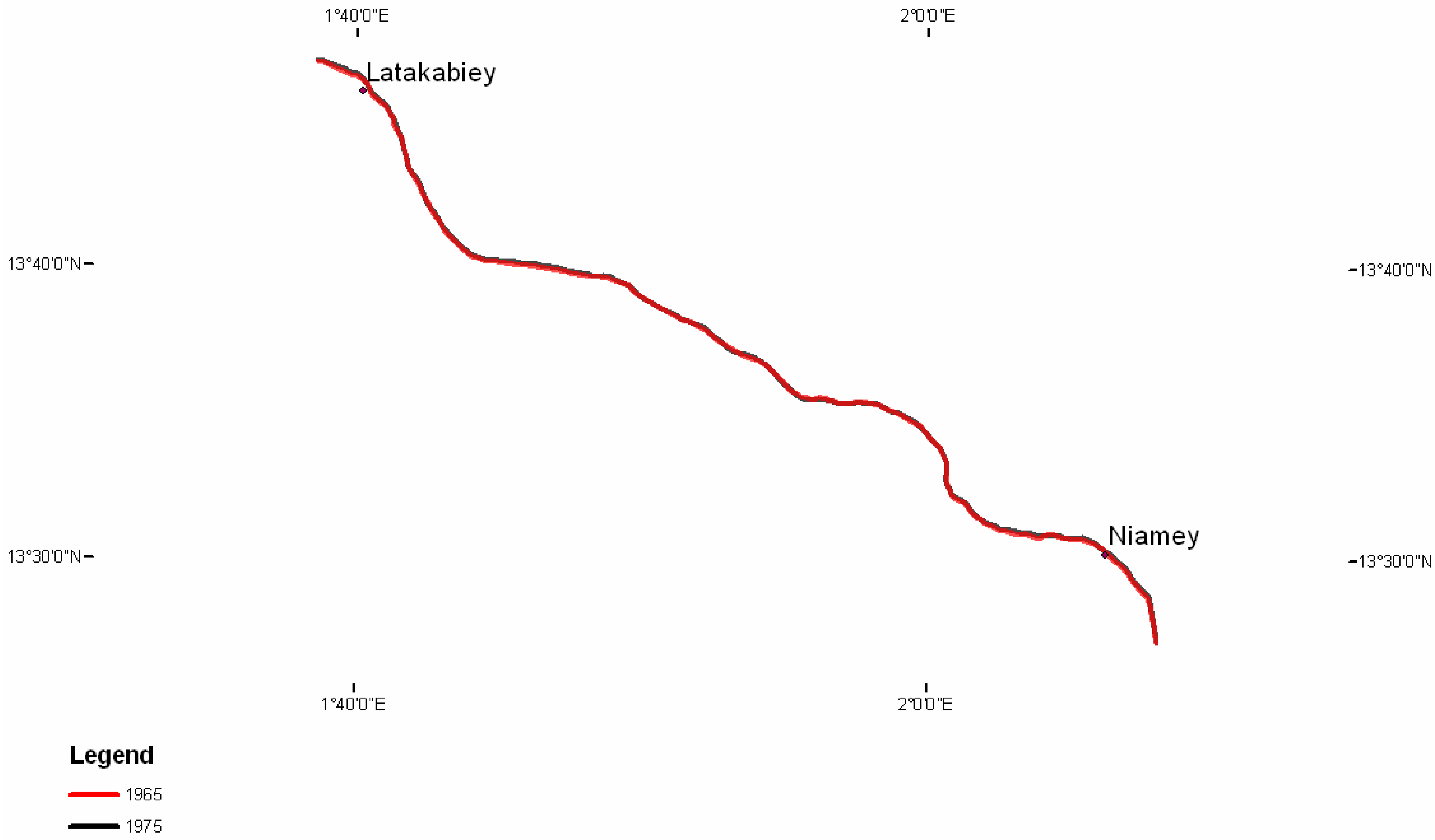


Figure B- 68: River centre line change in reach 2 (1965 – 1975)

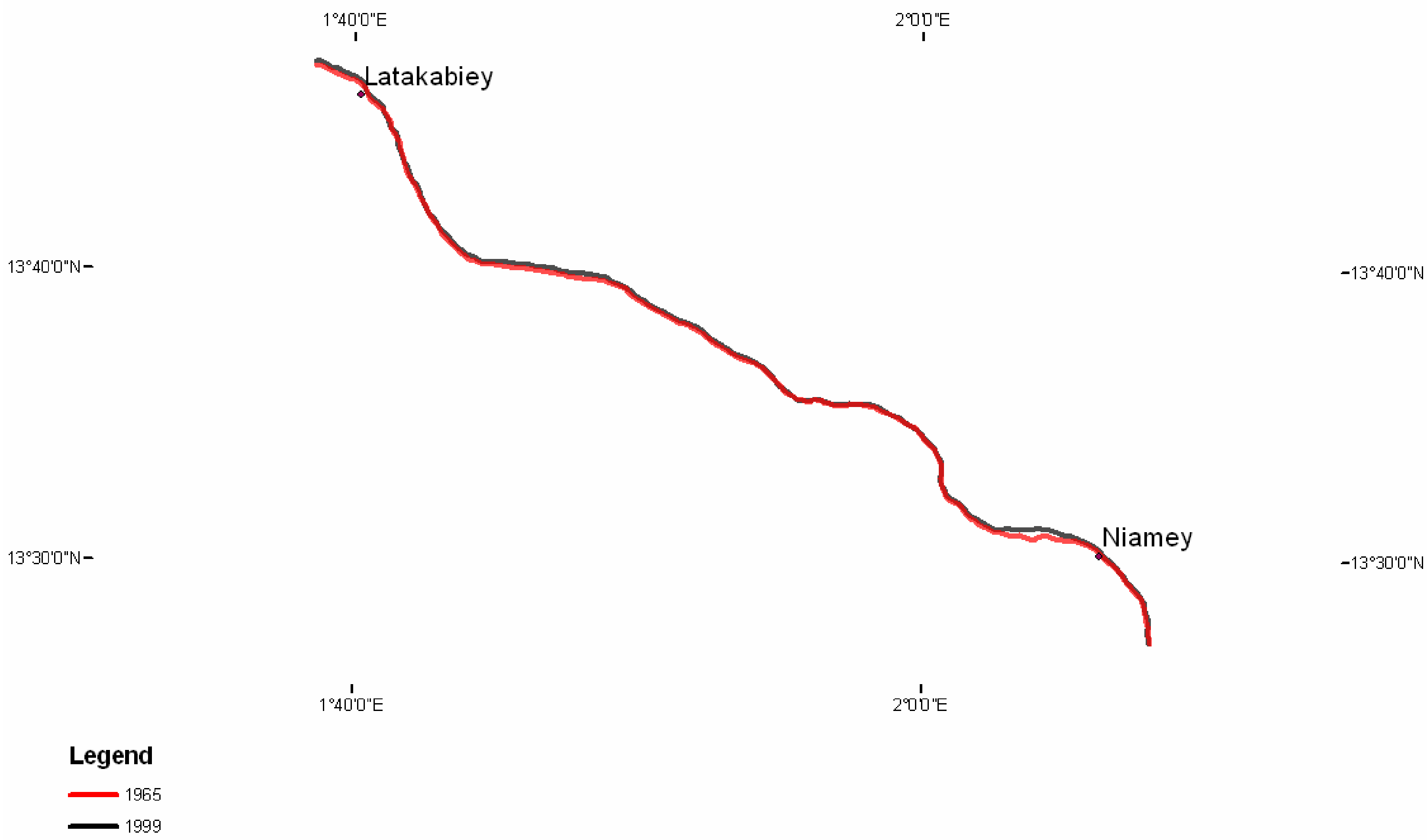


Figure B- 69: River centre line change in reach 2 (1965 – 1999)

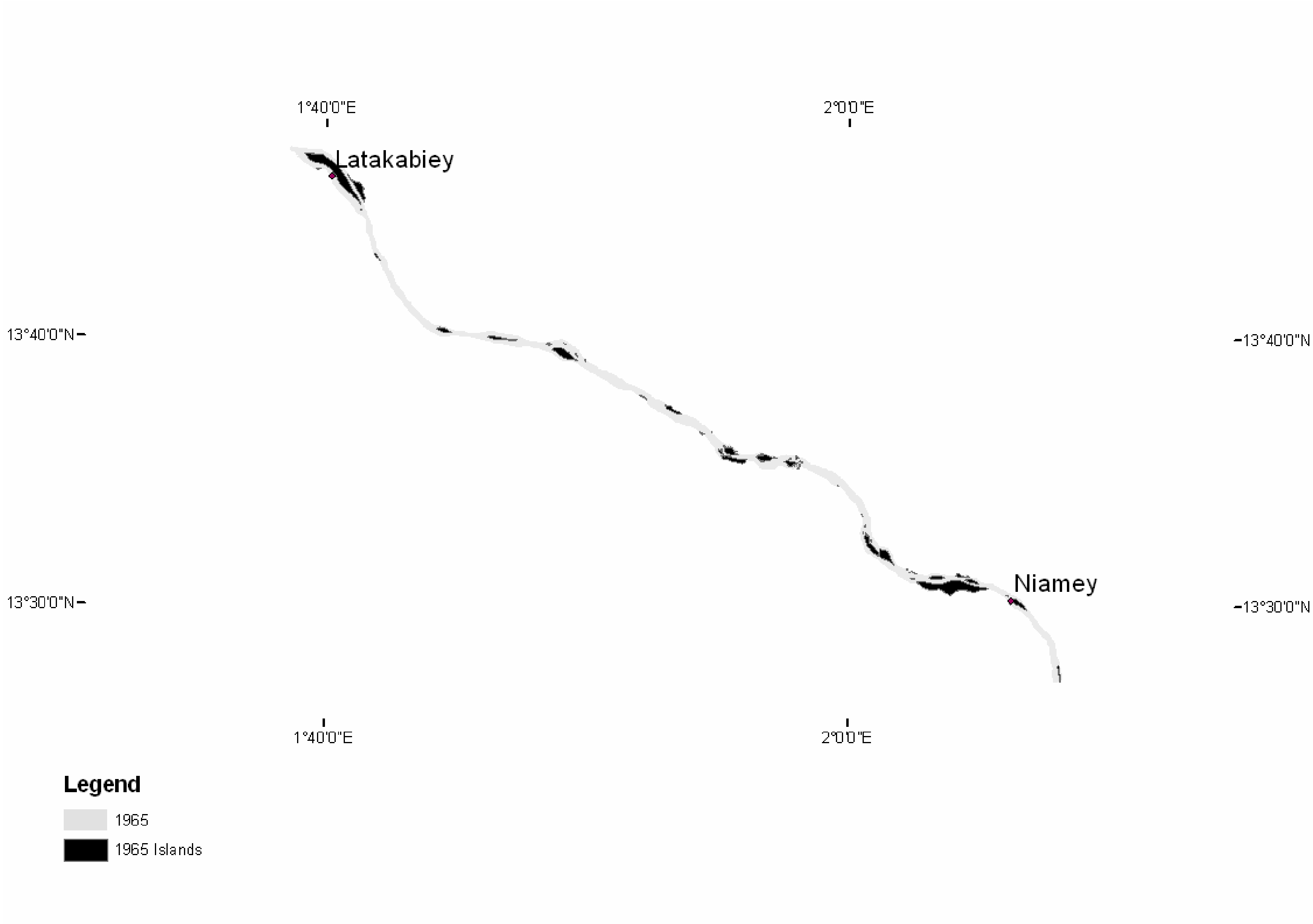


Figure B- 70: Reach 2 channel bank and island extents in 1965

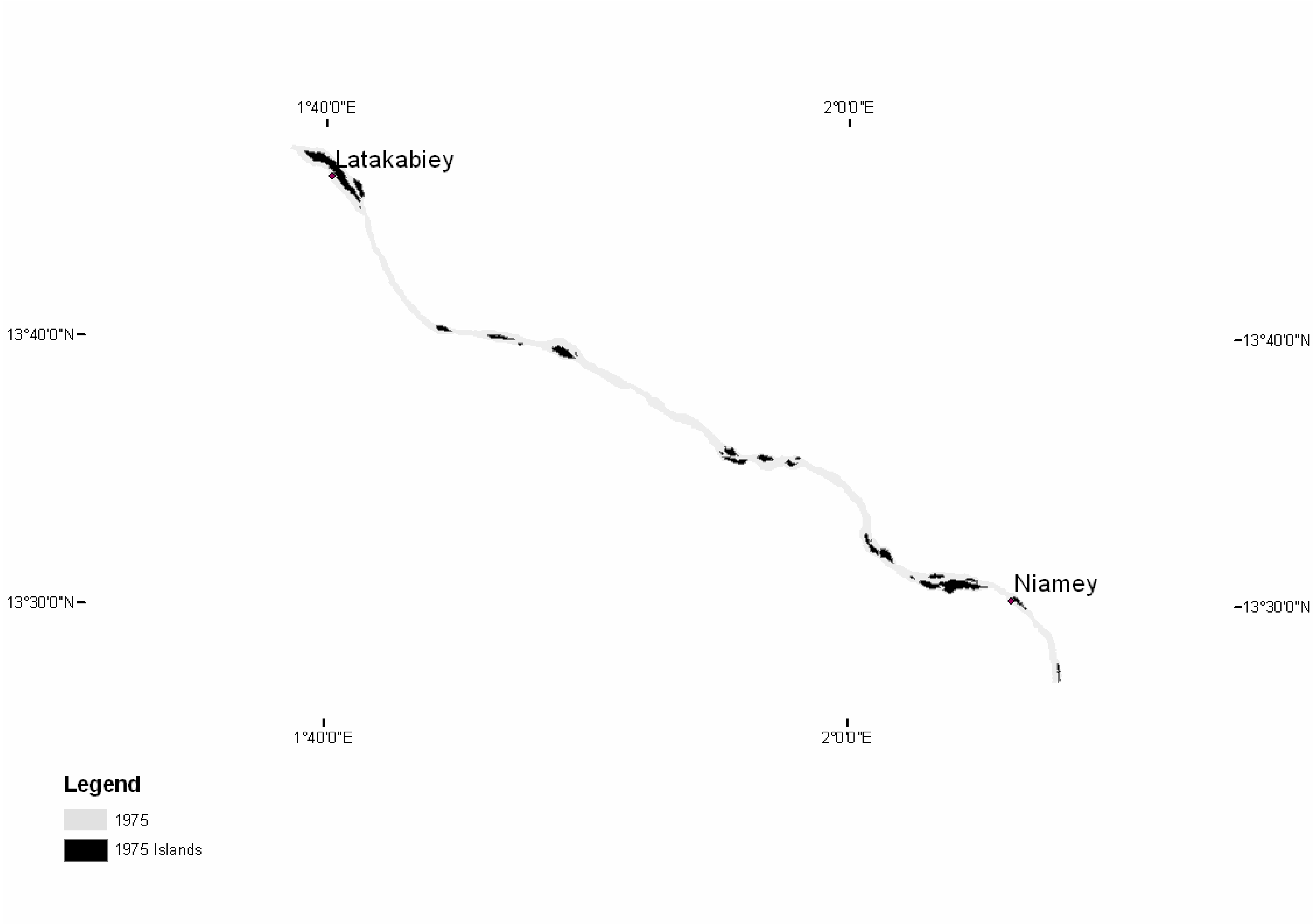


Figure B- 71: Reach 2 channel bank and island extents in 1975

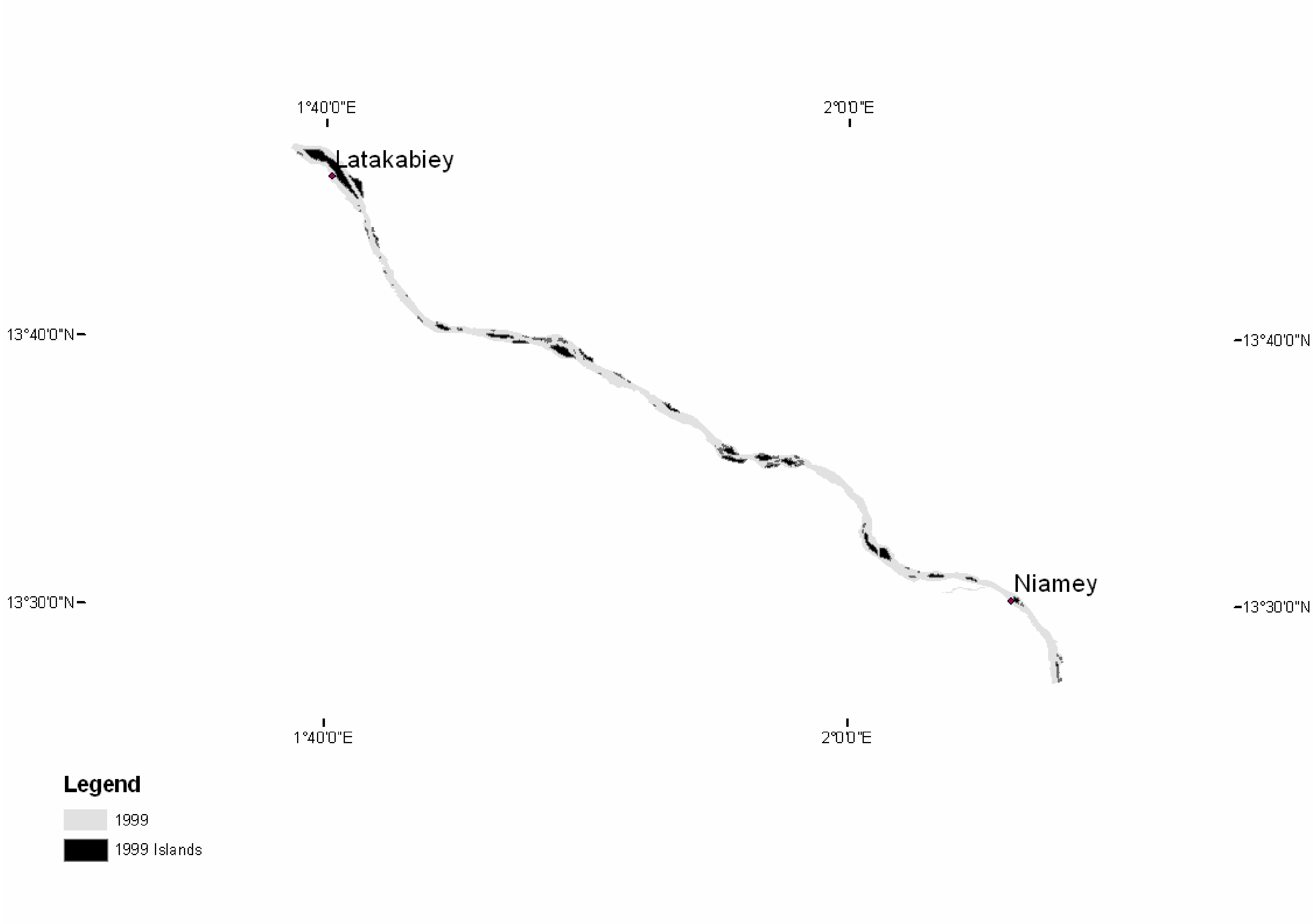


Figure B- 72: Reach 2 channel bank and island extents in 1999

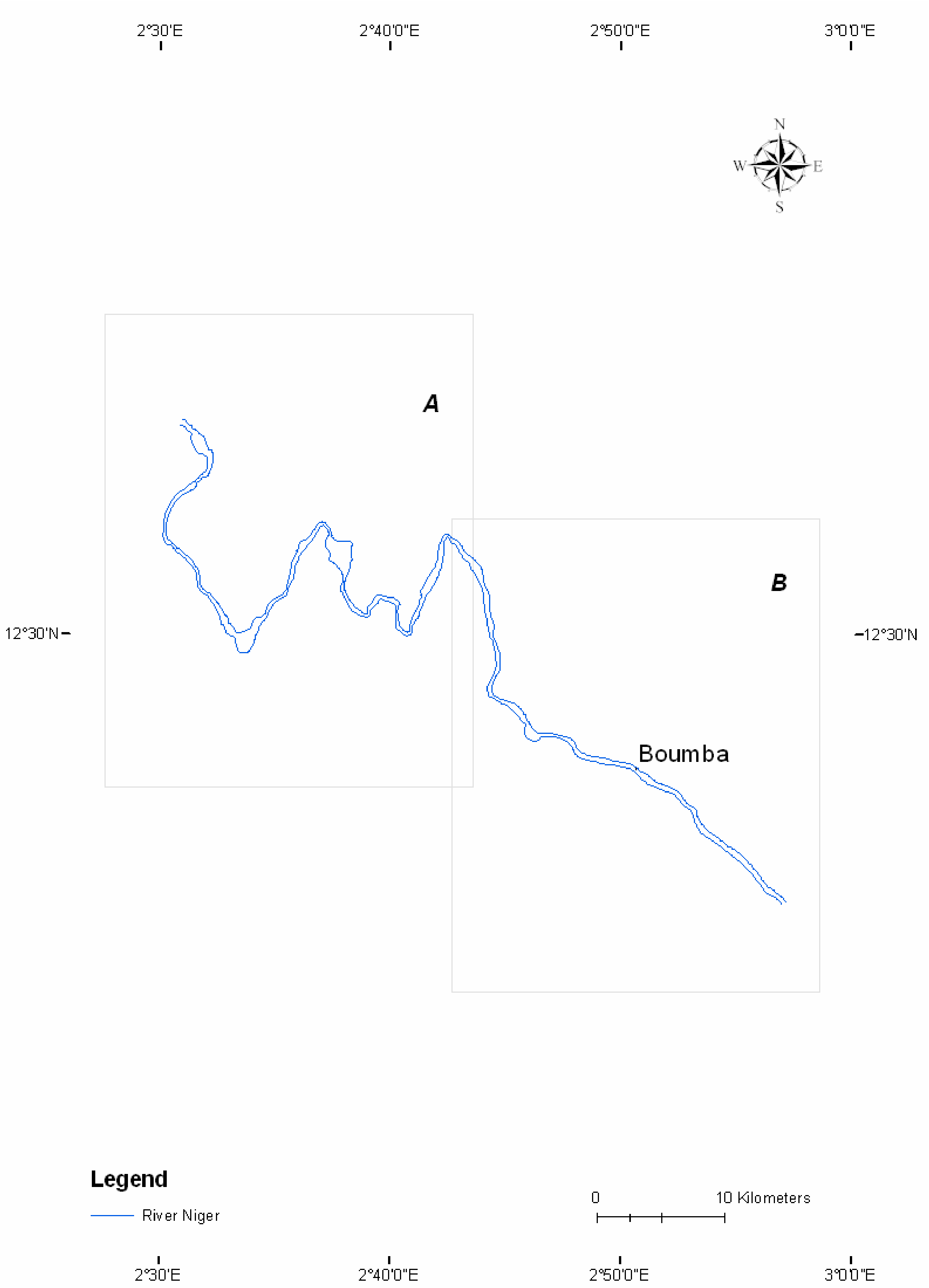


Figure B- 73 : Reach 3

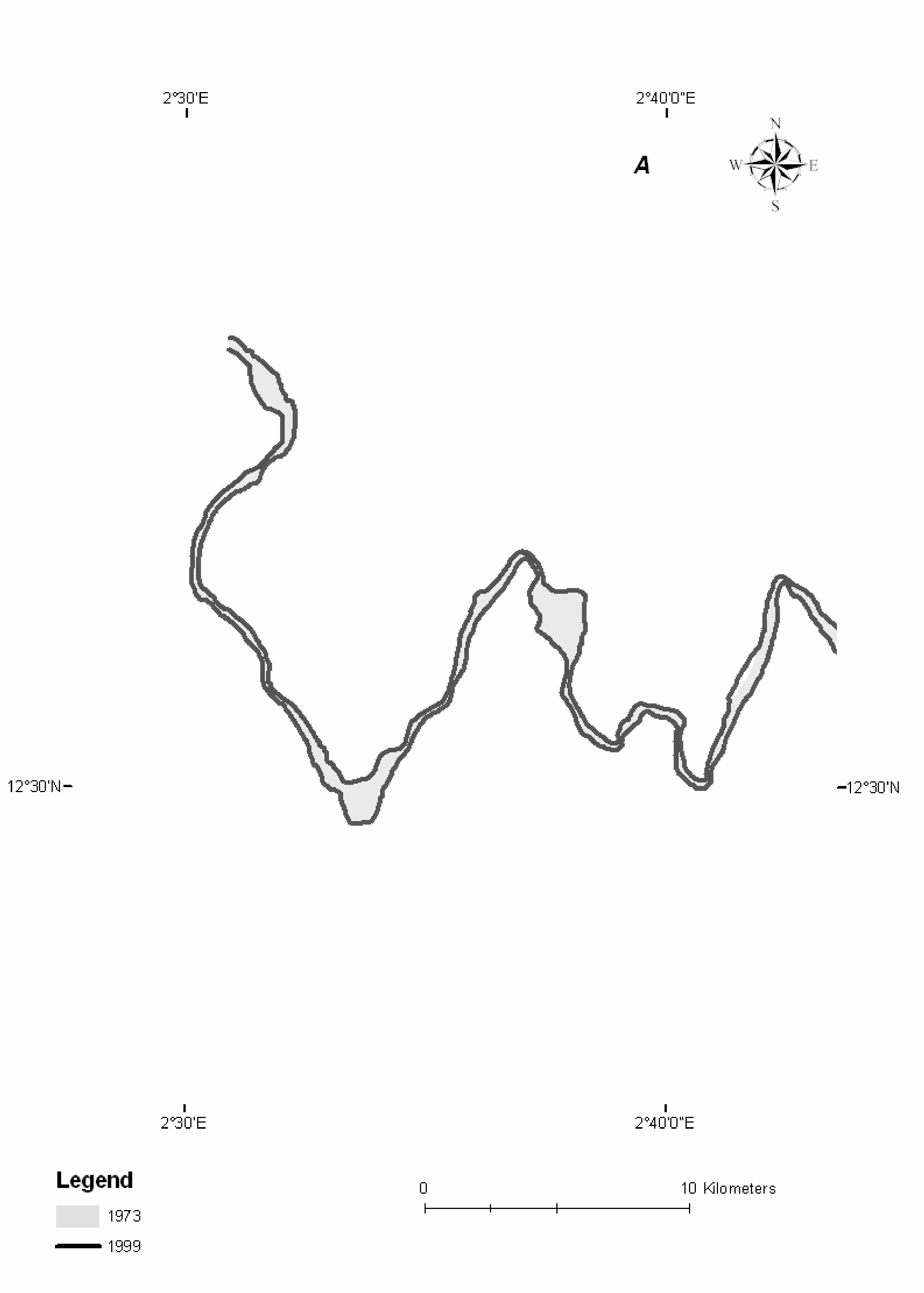


Figure B- 74A: Channel change in Reach 3 (1973-1999)

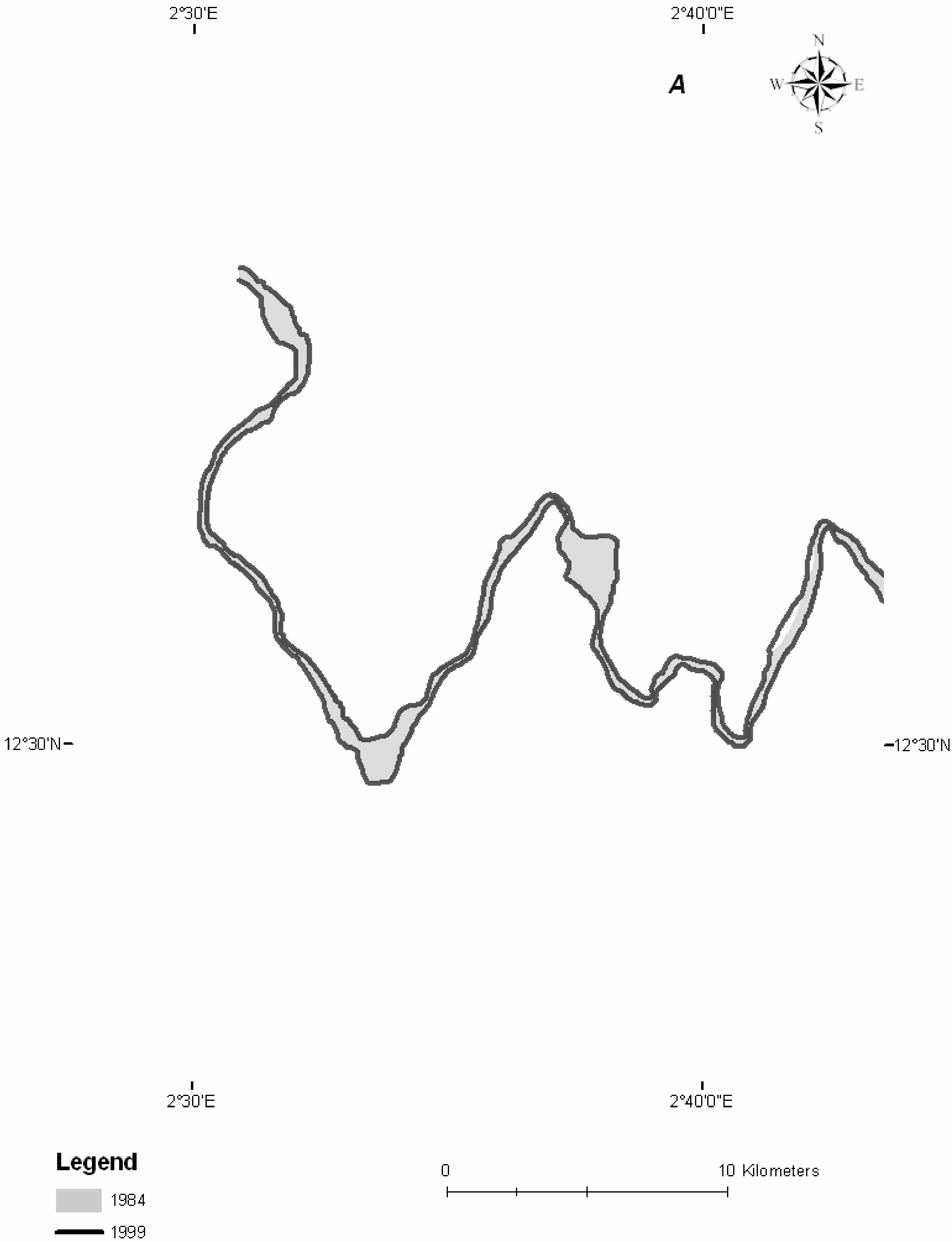


Figure B- 75A: Channel change in Reach 3 (1984-1999)

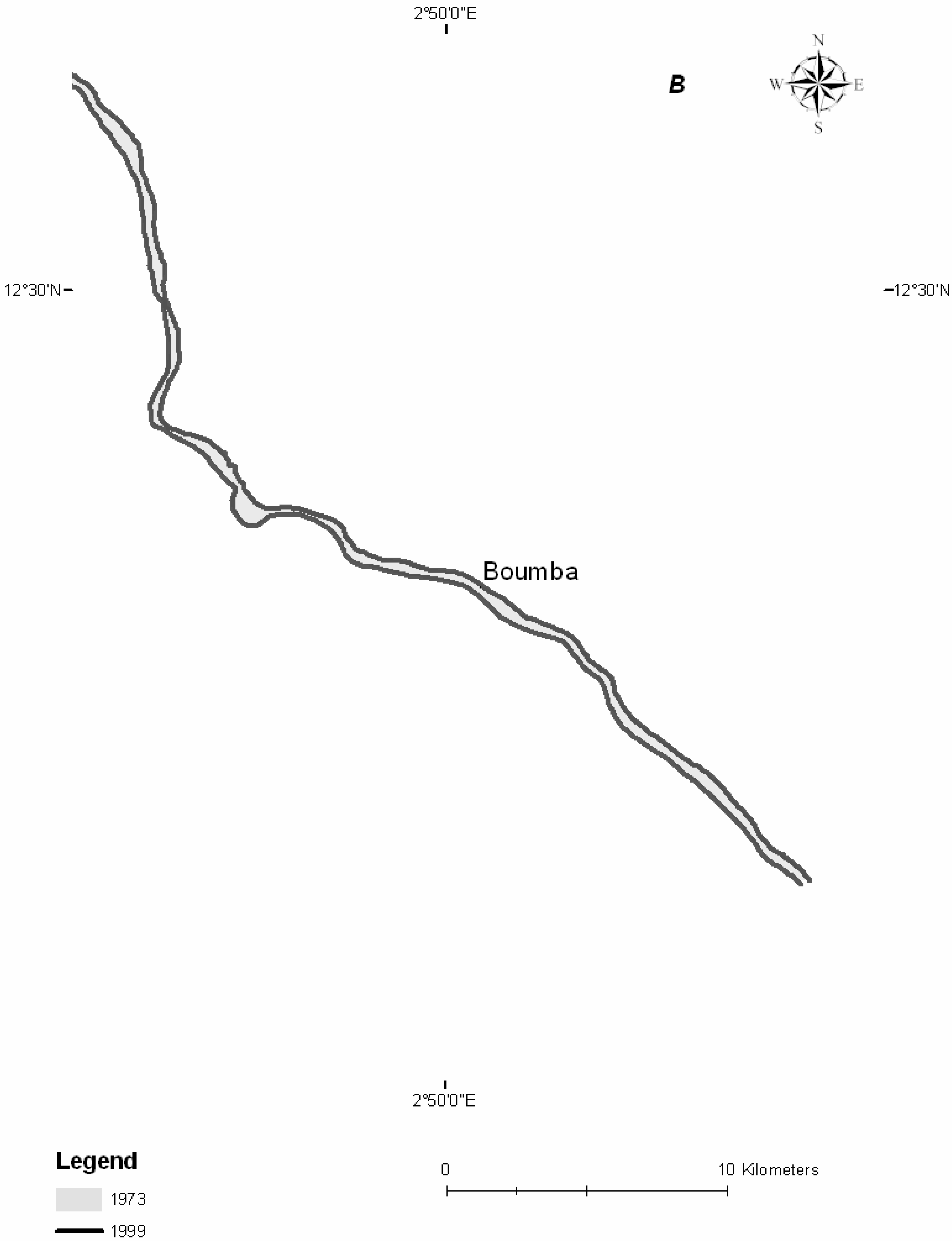


Figure B- 76B: Channel change in Reach 3 (1973-1999)

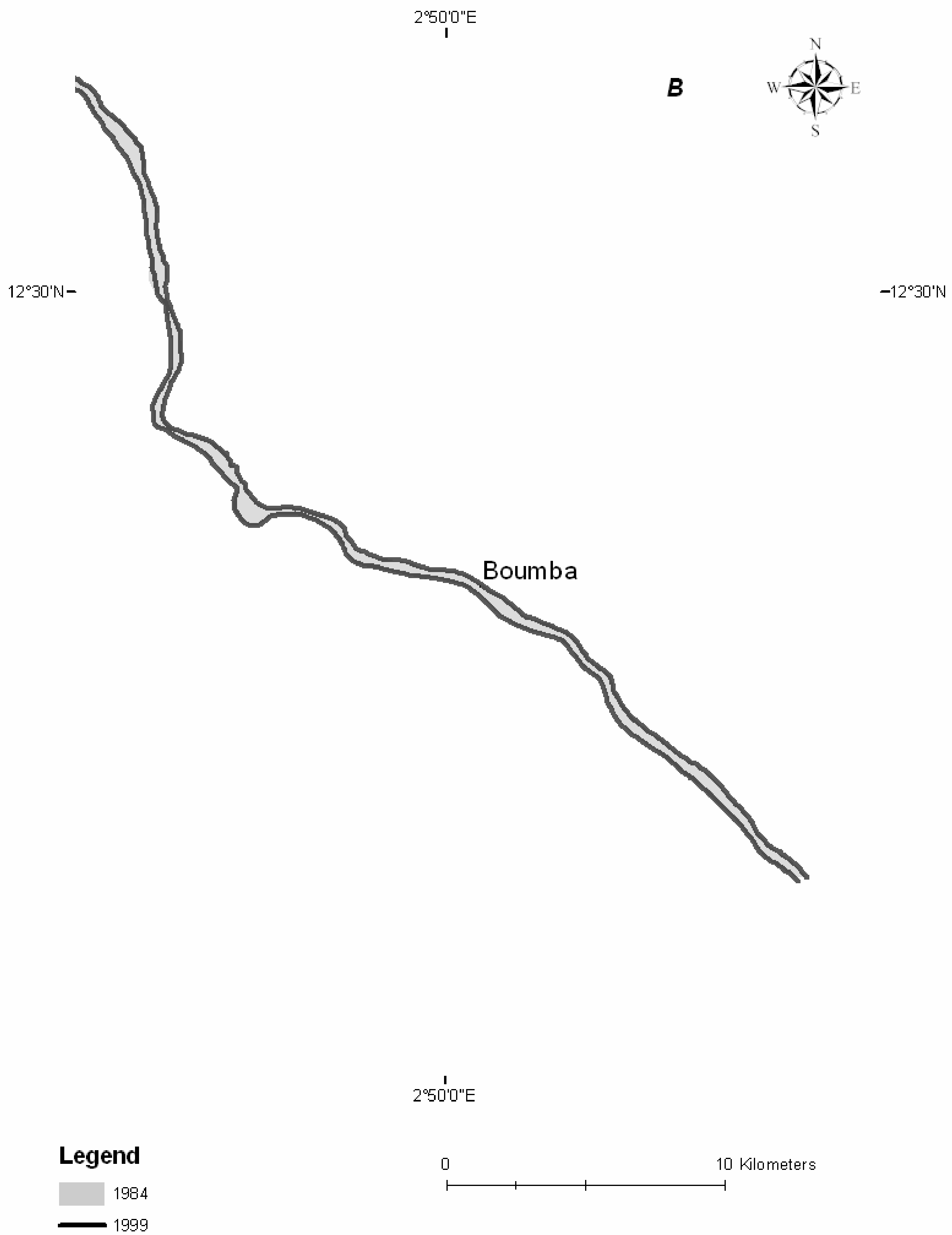


Figure B- 77B: Channel change in Reach 3 (1984-1999)

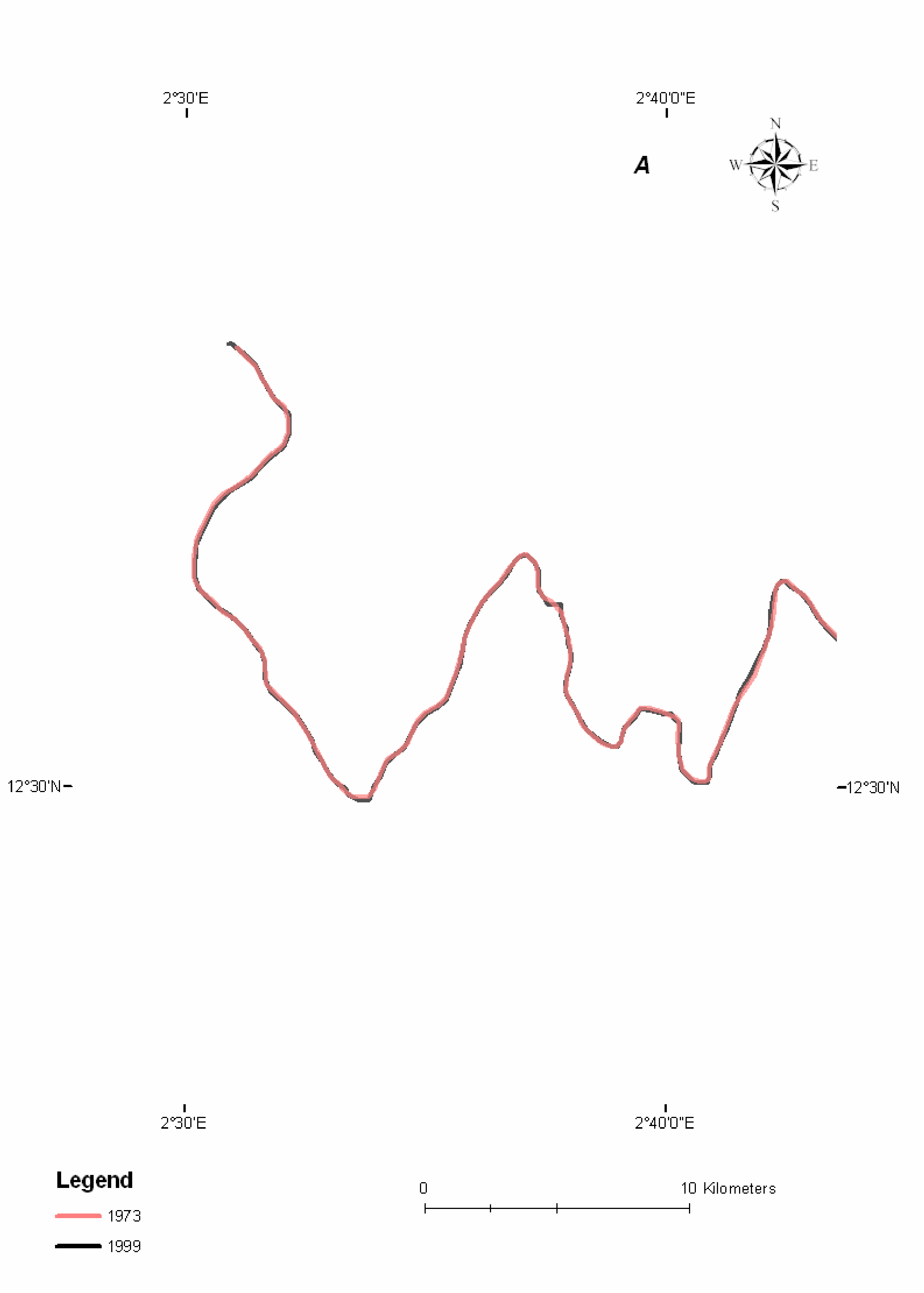


Figure B- 78A: River centre line change in reach 3 (1973 – 1999)

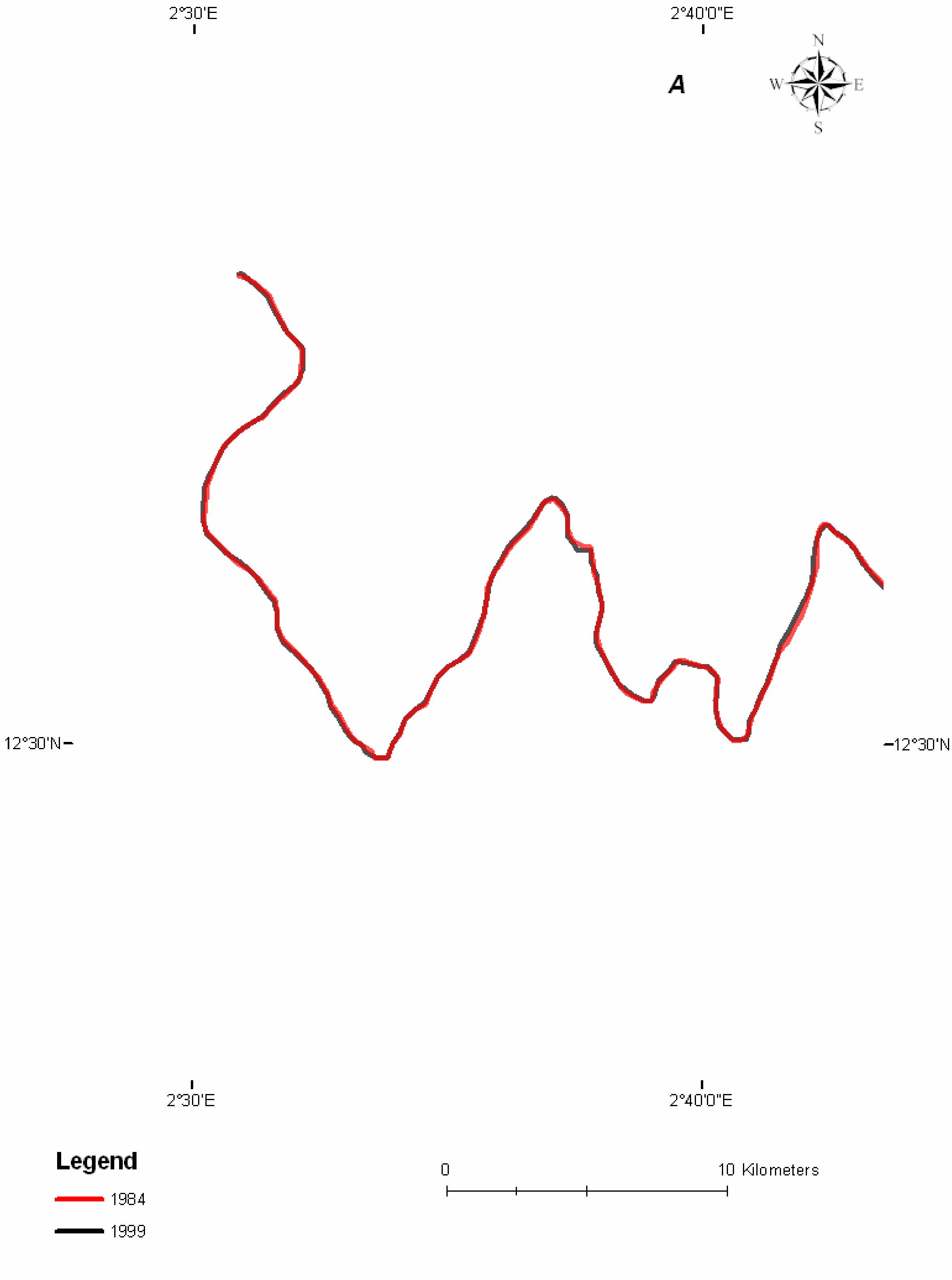


Figure B- 79A: River centre line change in reach 3 (1984 – 1999)

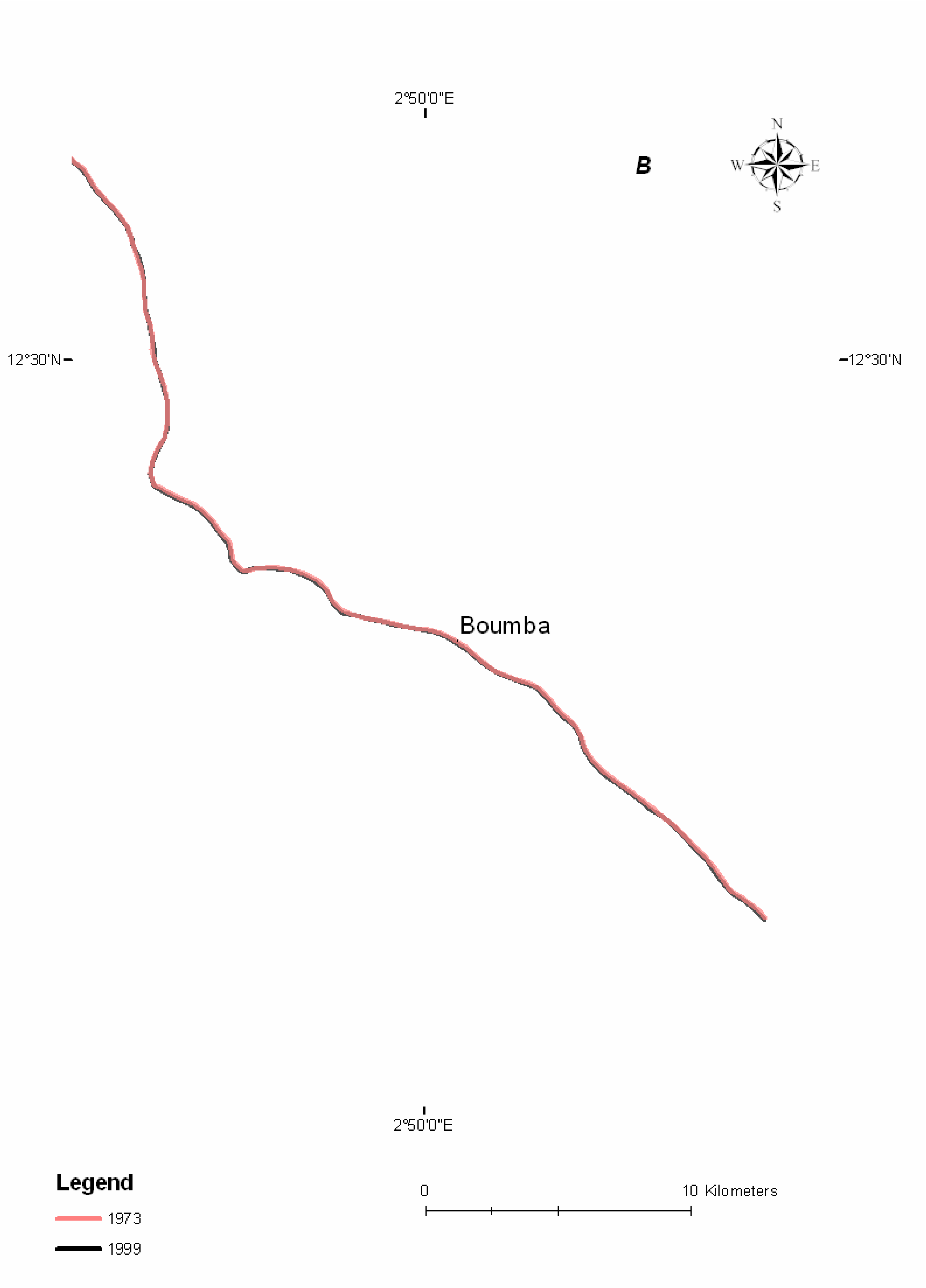


Figure B- 80B: River centre line change in reach 3 (1973 – 1999)

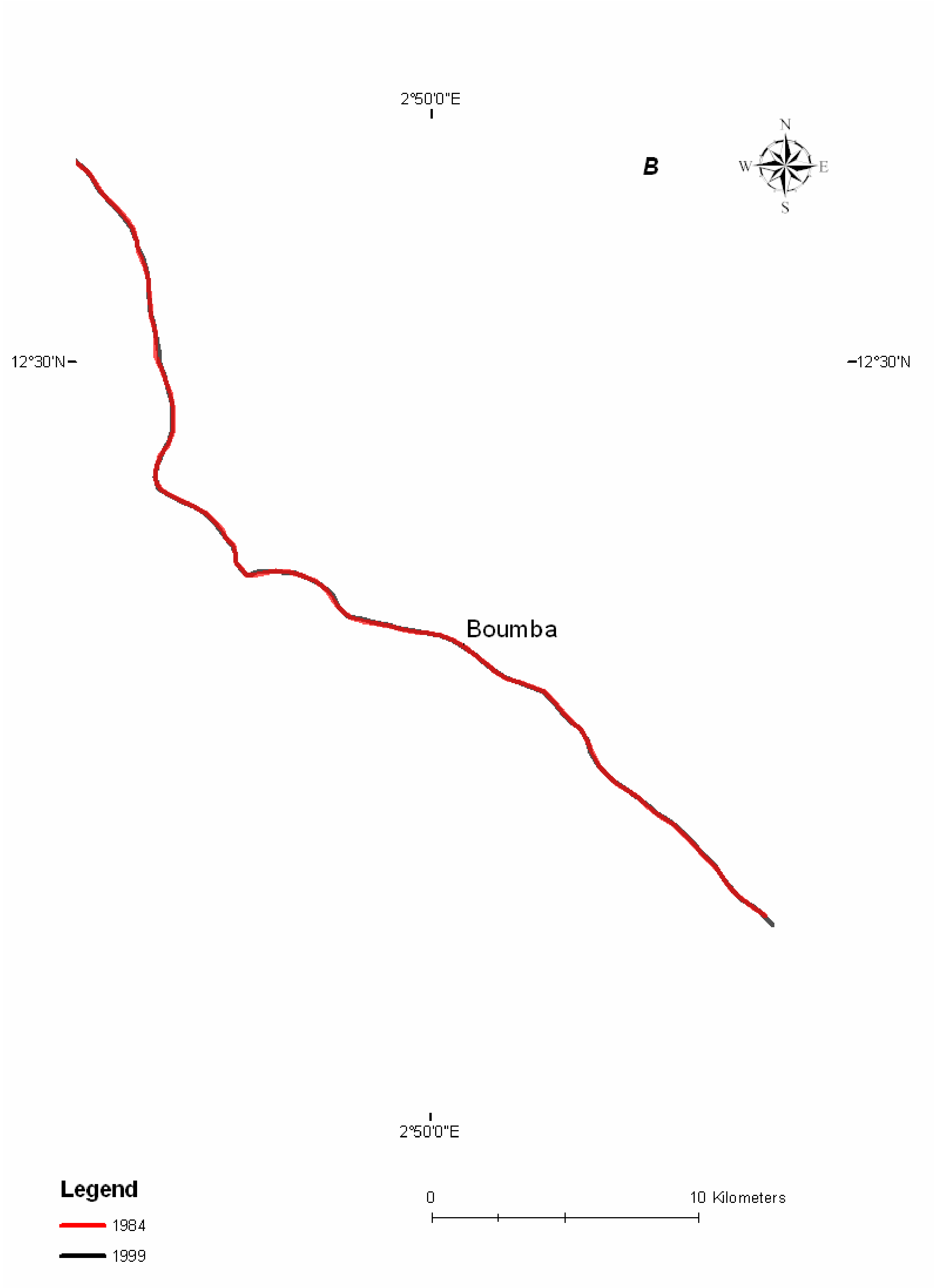


Figure B- 81B: River centre line change in reach 3 (1984 – 1999)

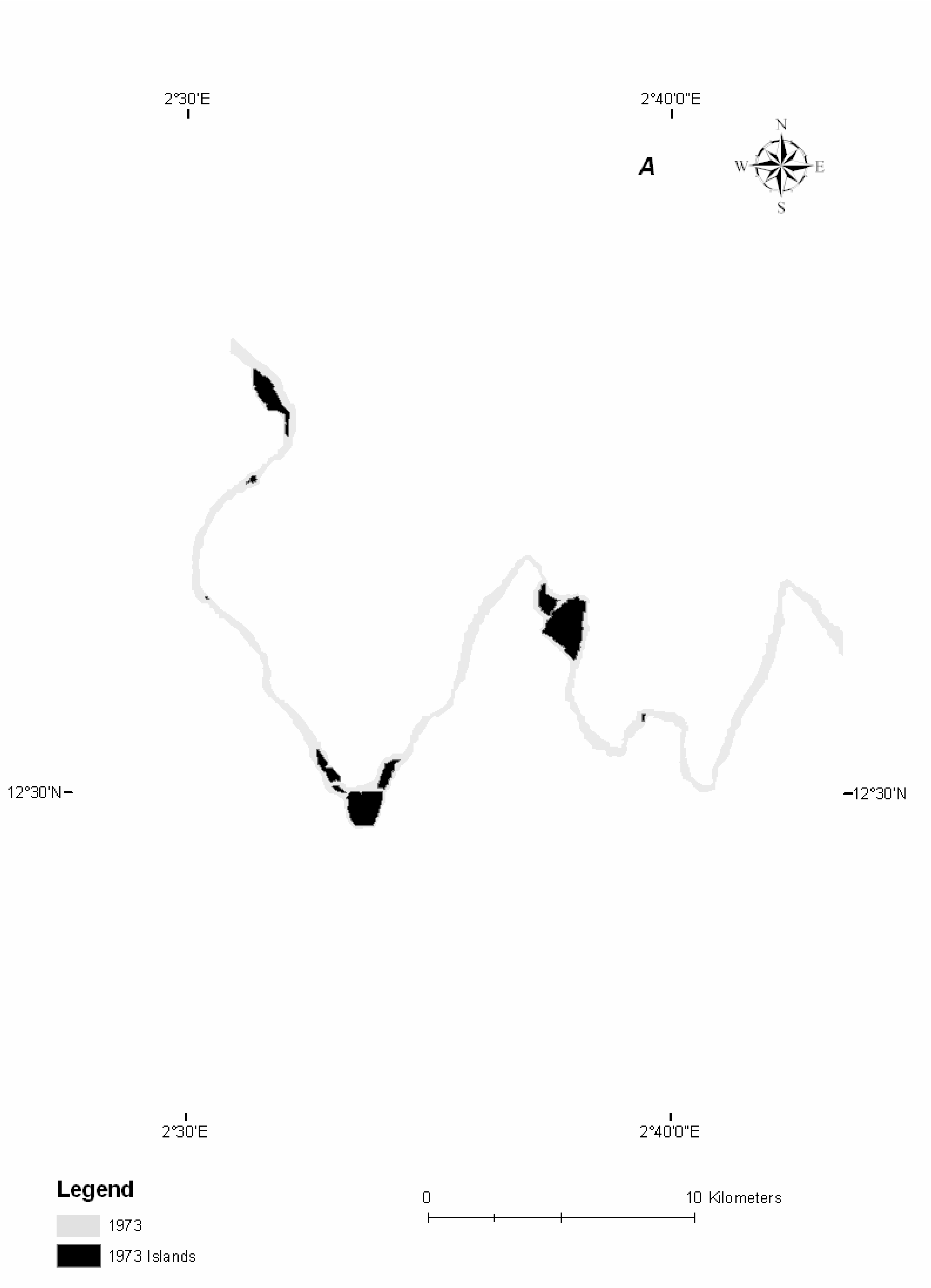


Figure B- 82A: Reach 3 channel bank and island extents in 1973

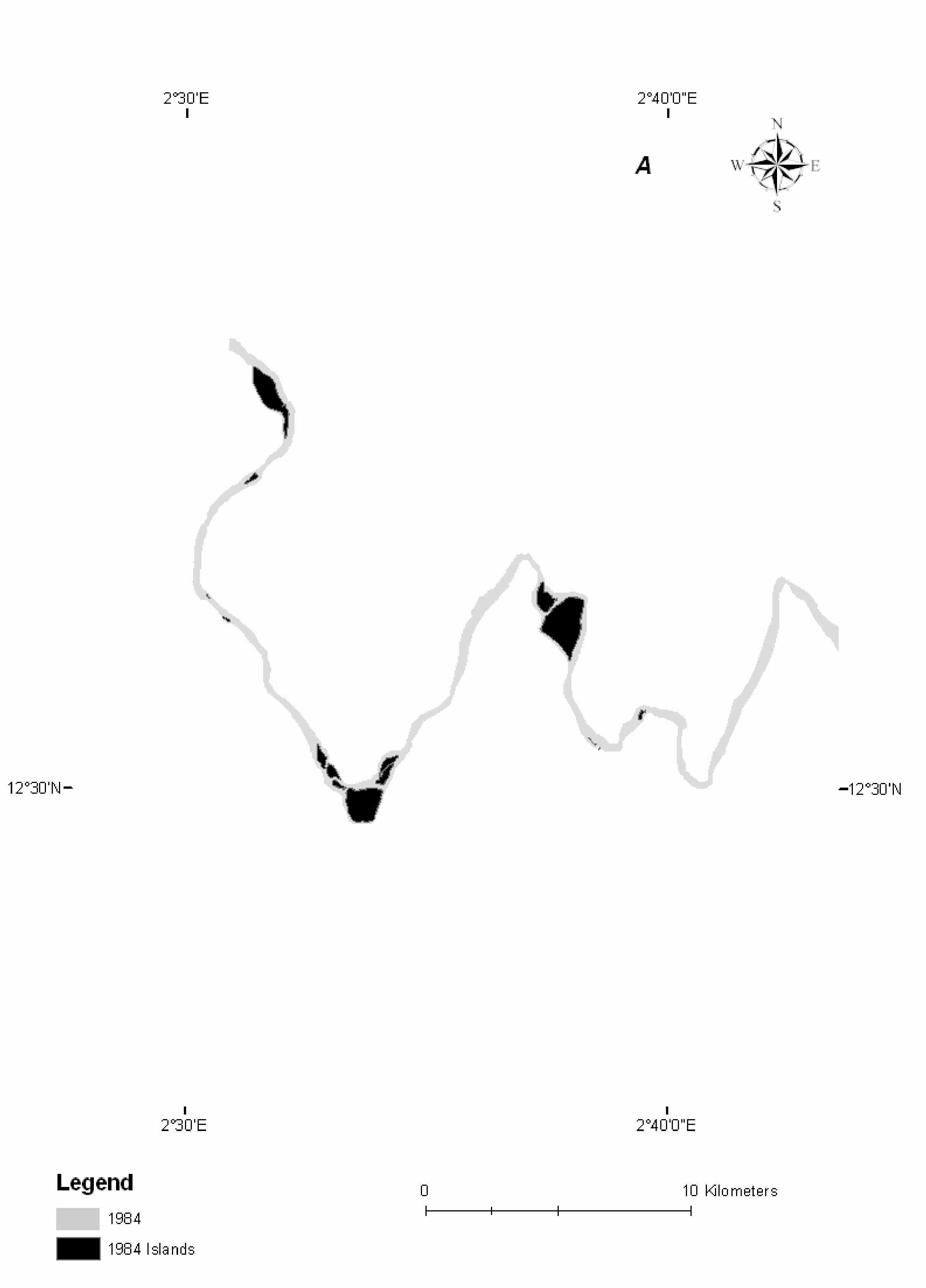


Figure B- 83A: Reach 3 channel bank and island extents in 1984

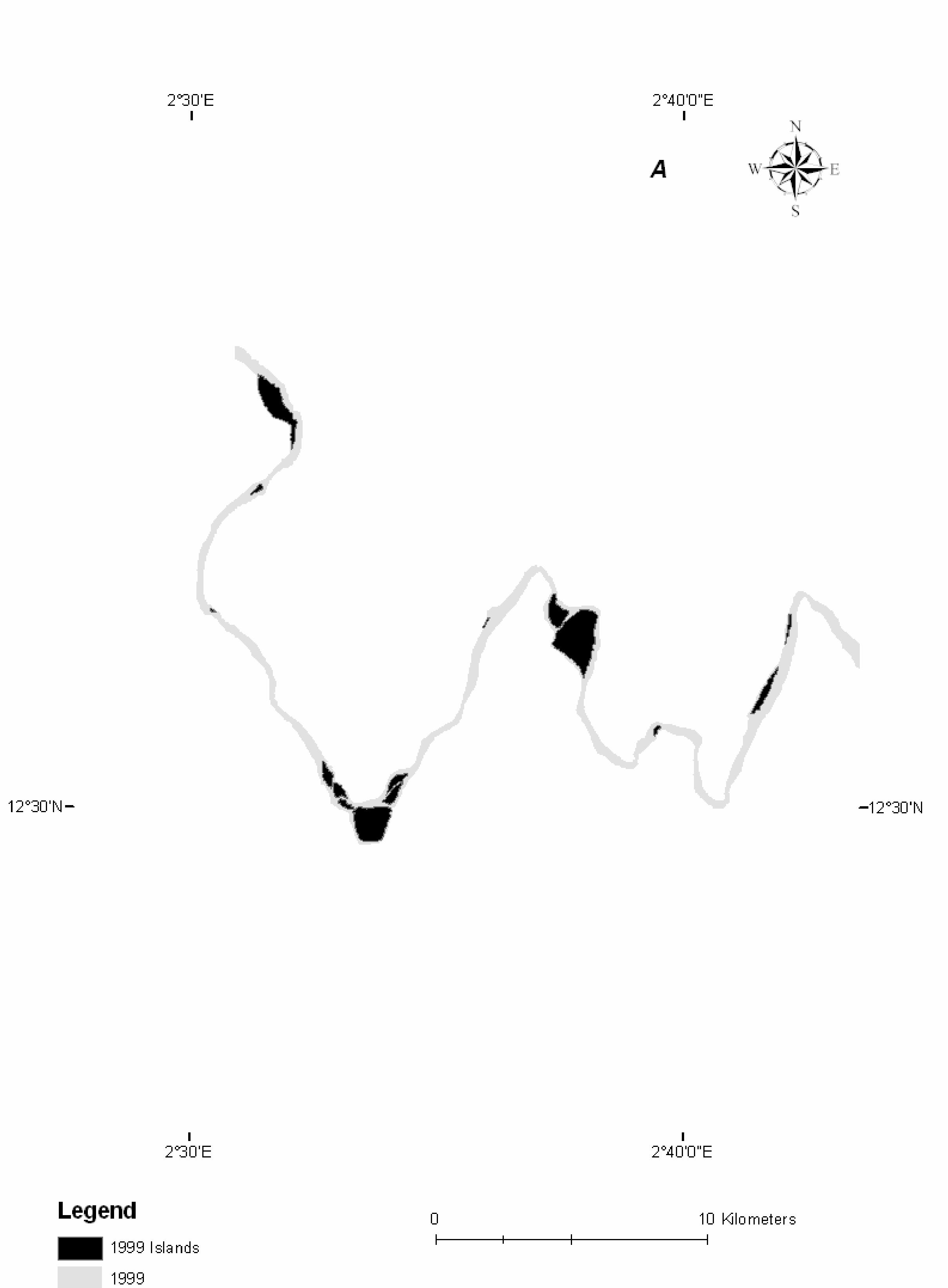


Figure B- 84A: Reach 3 channel bank and island extents in 1999

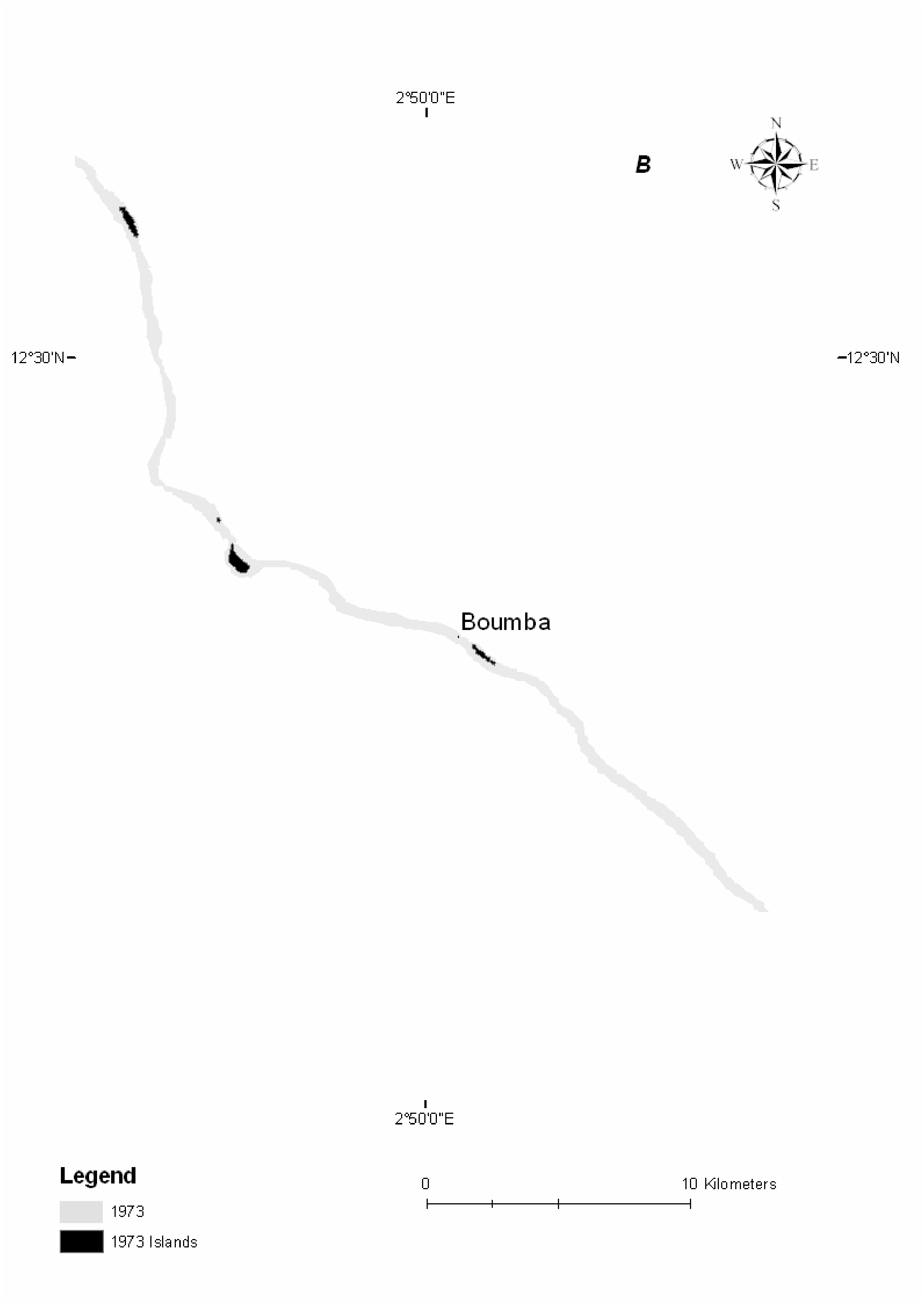


Figure B- 85B: Reach 3 channel bank and island extents in 1973

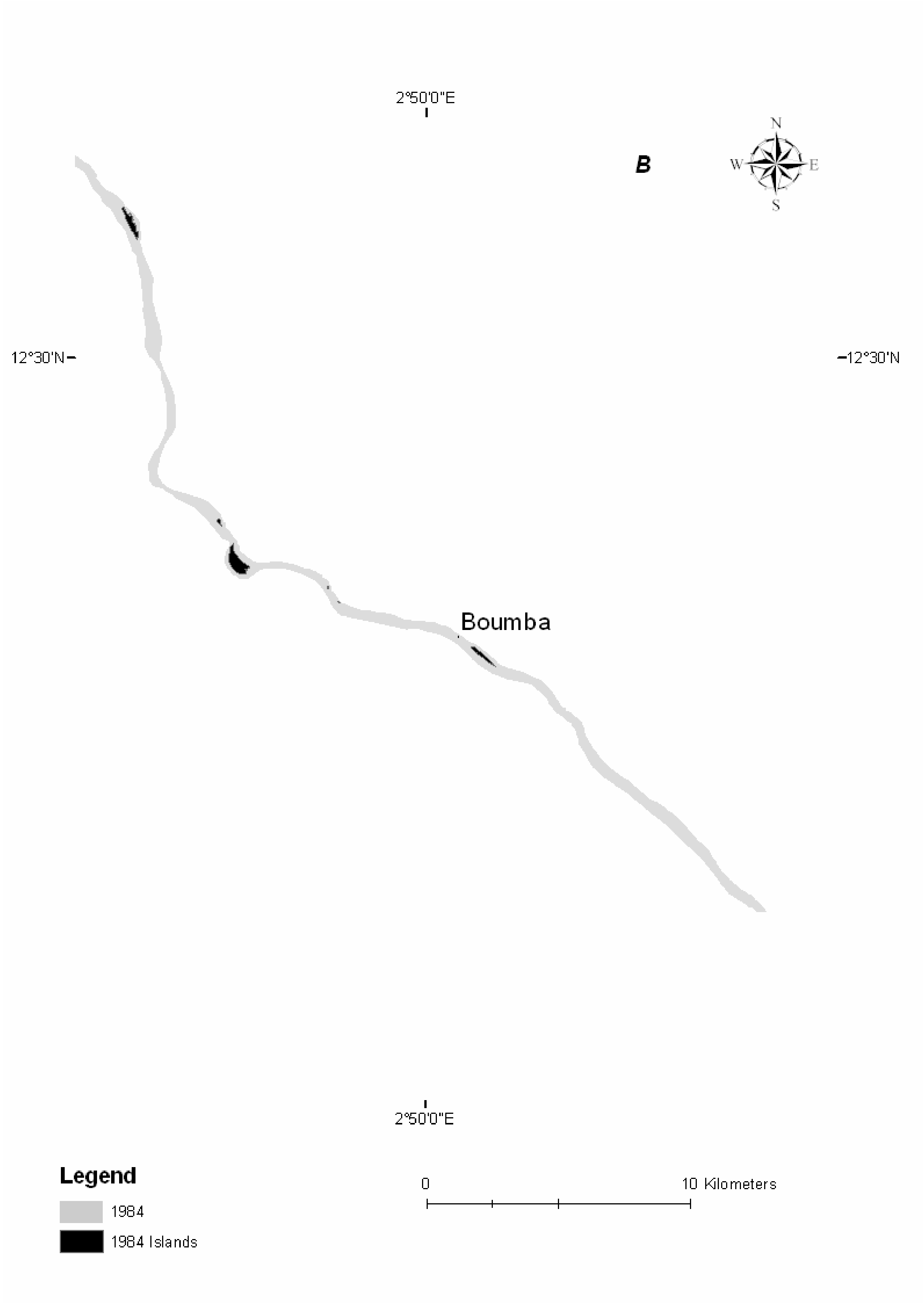


Figure B- 86B: Reach 3 channel bank and island extents in 1984

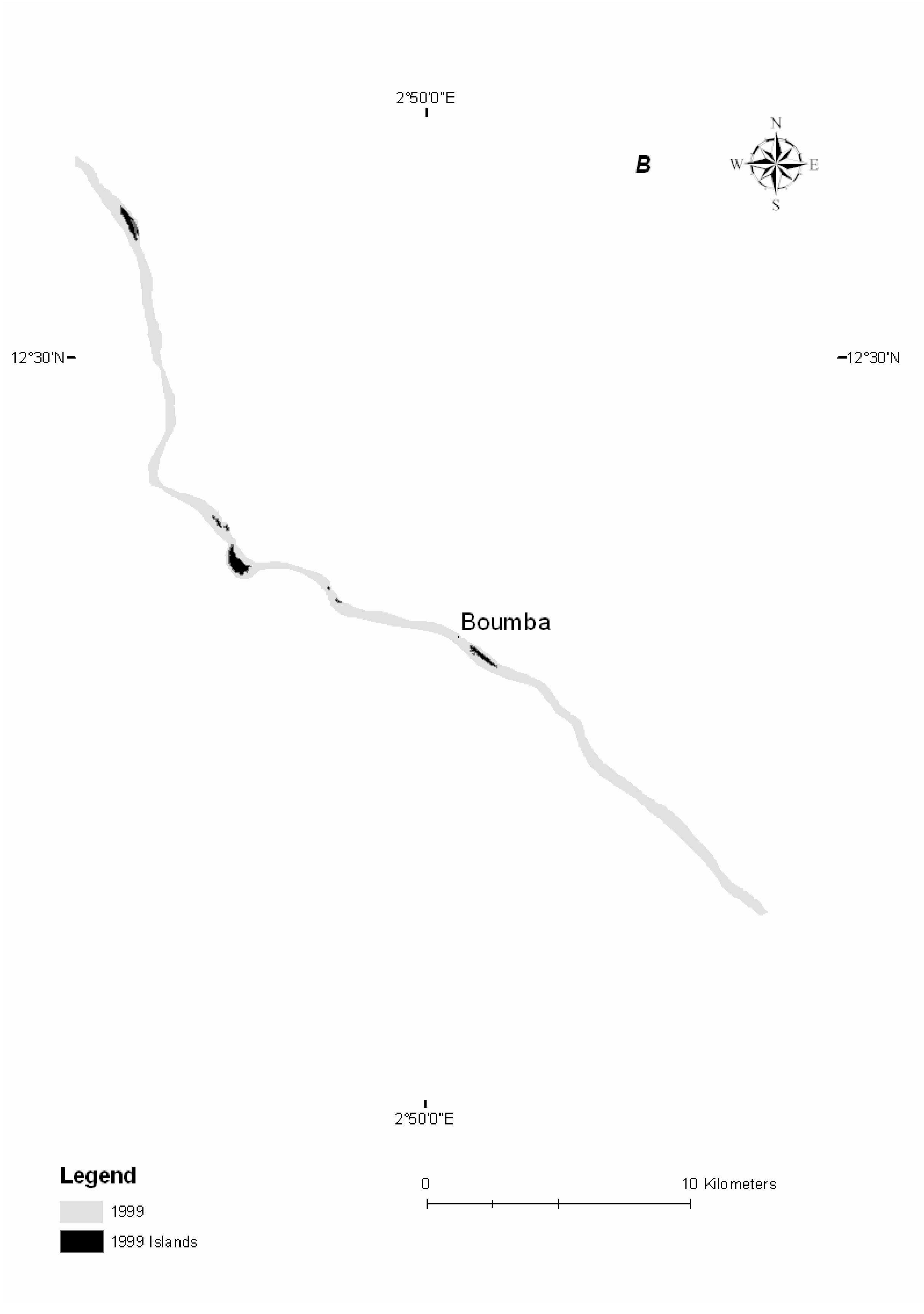


Figure B- 87B: Reach 3 channel bank and island extents in 1999

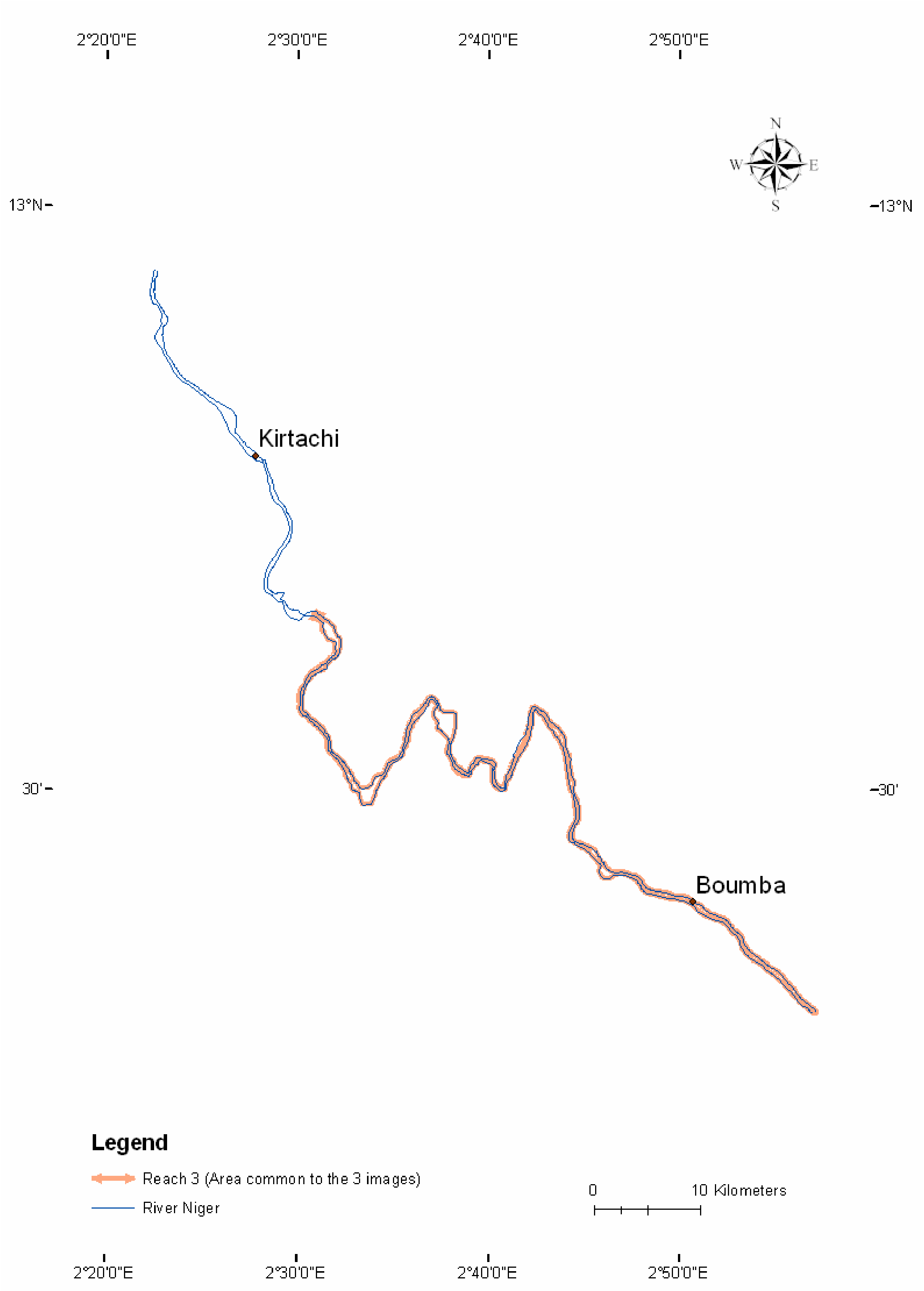


Figure B- 88: Extent of additional image data (1984 and 1999) overlaid by data used for reach 3

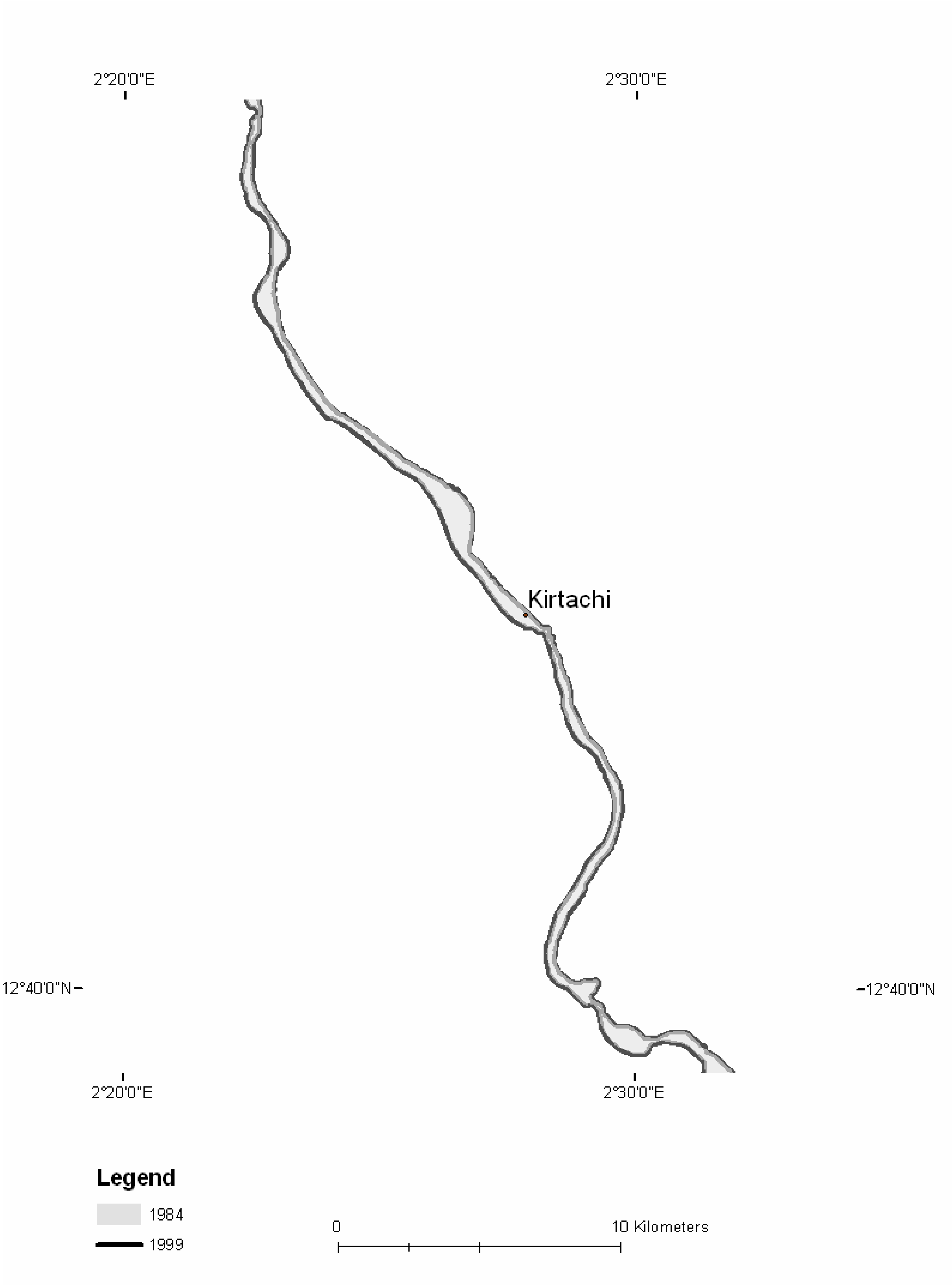


Figure B- 89: Channel change (1984-1999)

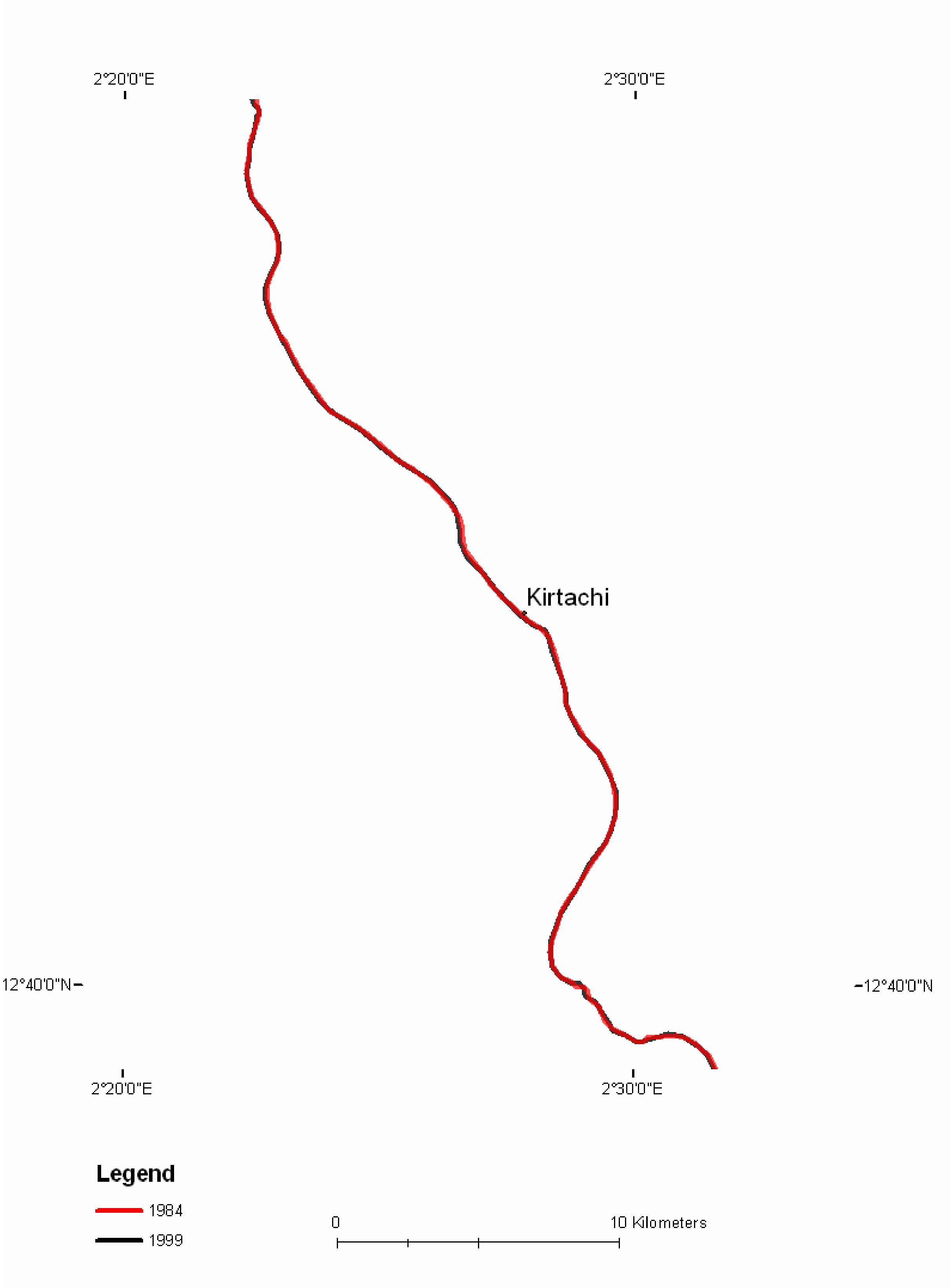


Figure B- 90 : River centre line change (1984 – 1999)

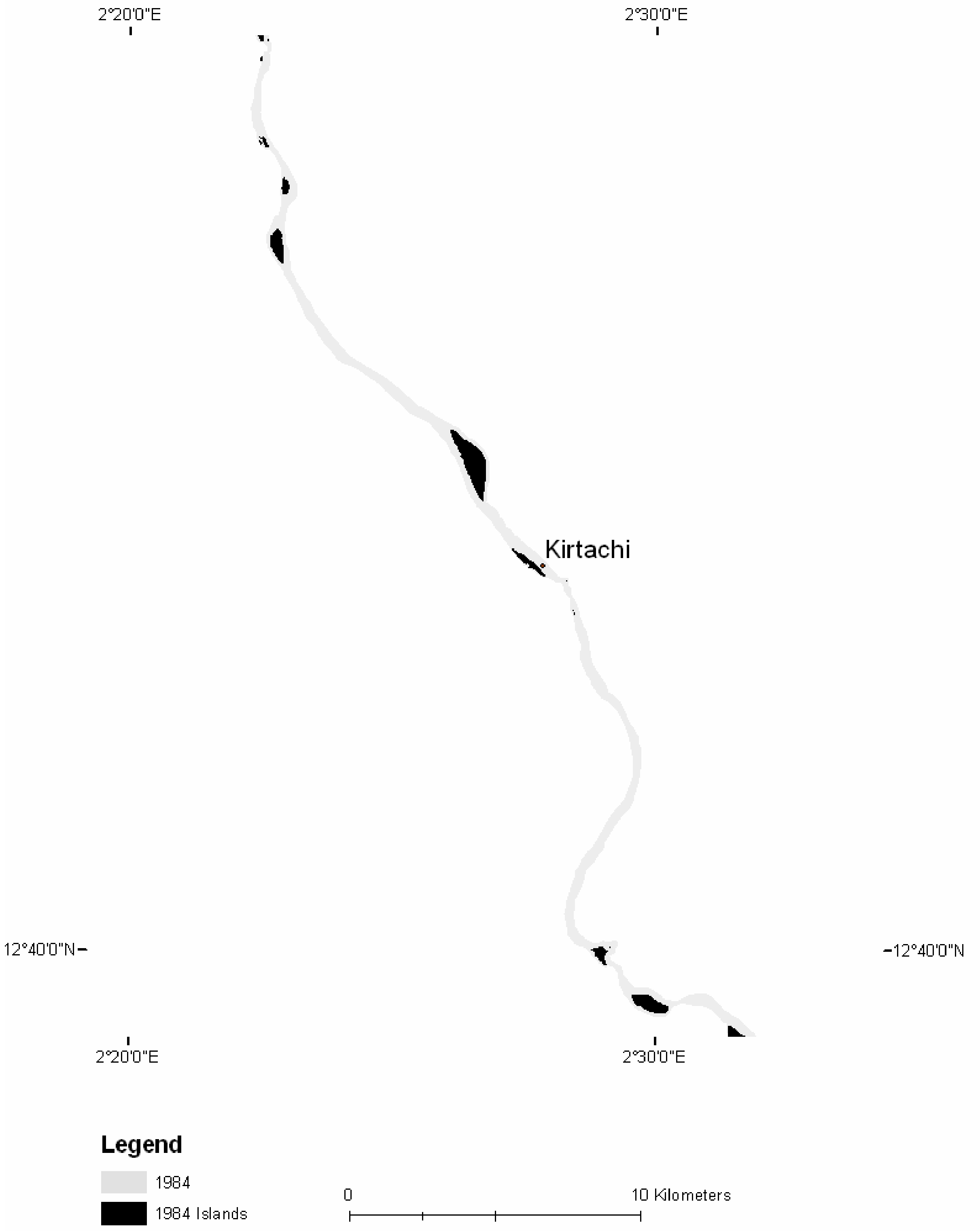


Figure B- 91: Channel bank and island extents in 1984

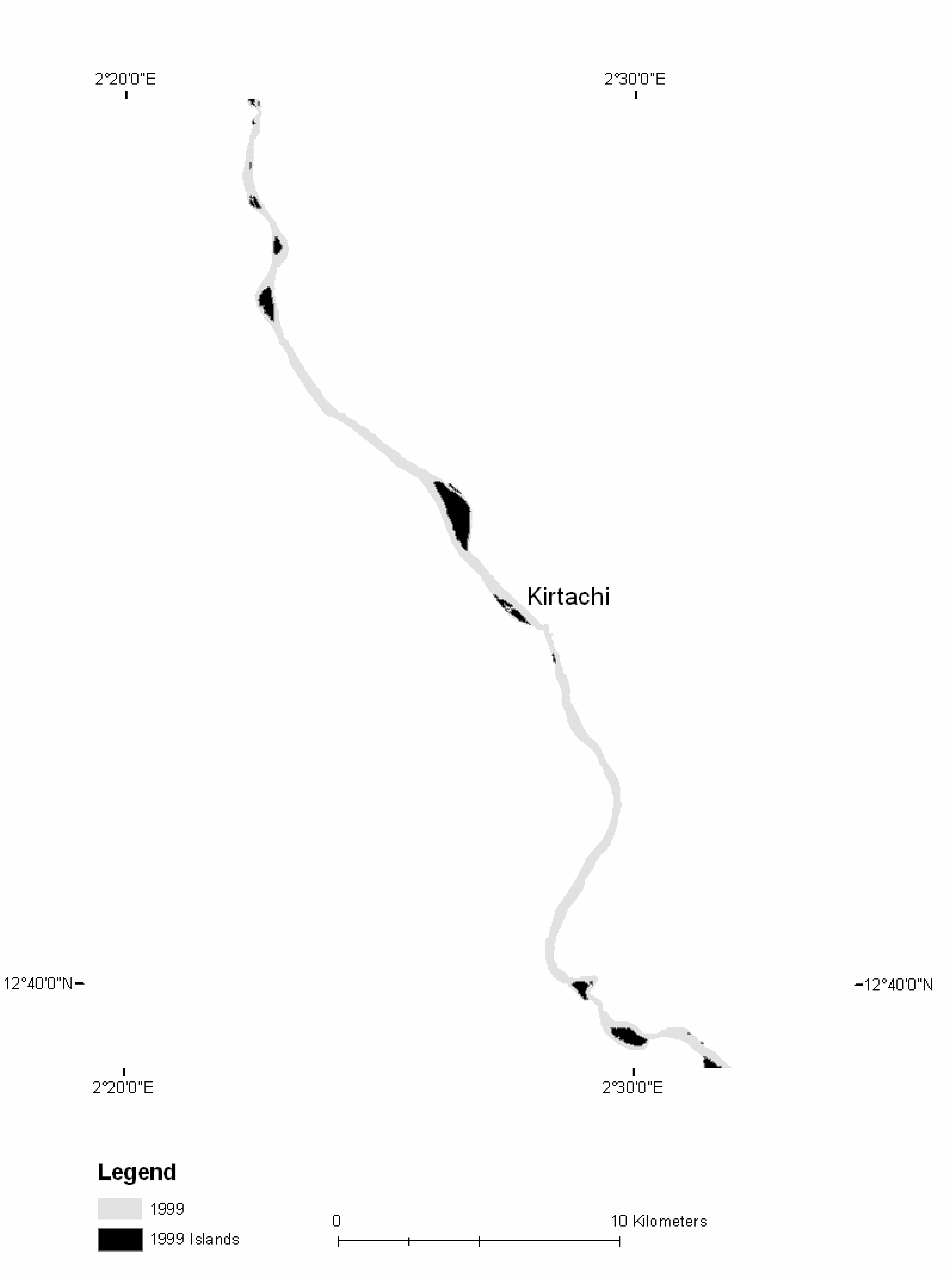


Figure B- 92: Channel bank and island extents in 1999

Table B- 1: Reach 1

KM	1979-1984	1984-1992	1992-1999
0	73.32499	68.63963	37.65697
10	451.65971	508.50797	31.73437
20	47.17535	54.87828	76.52297
30	107.73281	159.29192	42.28044
40	170.81356	97.38798	12.15495
50	34.17144	22.31122	95.82385
60	23.06358	159.70448	60.75399
70	538.59981	28.32841	130.49057
80	55.38323	42.21761	101.68499
90	102.60619	4.05394	4.45598
100	304.64561	105.12886	98.33704
110	159.45074	62.24519	43.34941
117	639.13859	235.82726	362.03854
MEAN	208.28966	119.11713	84.40647

Table B- 2: Reach 2

KM	1975-1984	1984-1989	1989-1999
0	121.39057	164.27960	24.02157
10	83.31583	7.65894	23.48117
20	23.45300	33.77922	55.65012
30	153.07795	124.00769	102.70341
40	35.63463	6.09415	69.97706
50	38.81491	58.60131	84.53913
60	3.41351	33.38837	7.68138
70	64.08248	46.18348	33.89292
80	44.90308	1.32734	16.99819
90	162.39981	93.73366	27.99191
100	12.92346	120.95807	106.89794
110	45.13623	63.03976	44.90799
120	11.27263	36.33891	51.18479
130	39.02835	3.56525	12.15924
140	783.84066	23.95807	80.19247
150	28.45404	7.72748	36.89705
MEAN	103.19632	51.54008	48.69852

Table B- 3: Reach 3

KM	1973-1984	1984-1999
0	20.15869	22.44857
10	100.32833	58.67460
20	48.35374	64.72050
30	28.41252	3.31476
40	13.79618	20.19822
50	41.86069	20.42645
60	26.89000	44.18578
70	30.70741	6.31353
80	72.55697	20.97125
90	20.89340	9.71145
100	377.98296	30.68554
MEAN	71.08554	27.42279

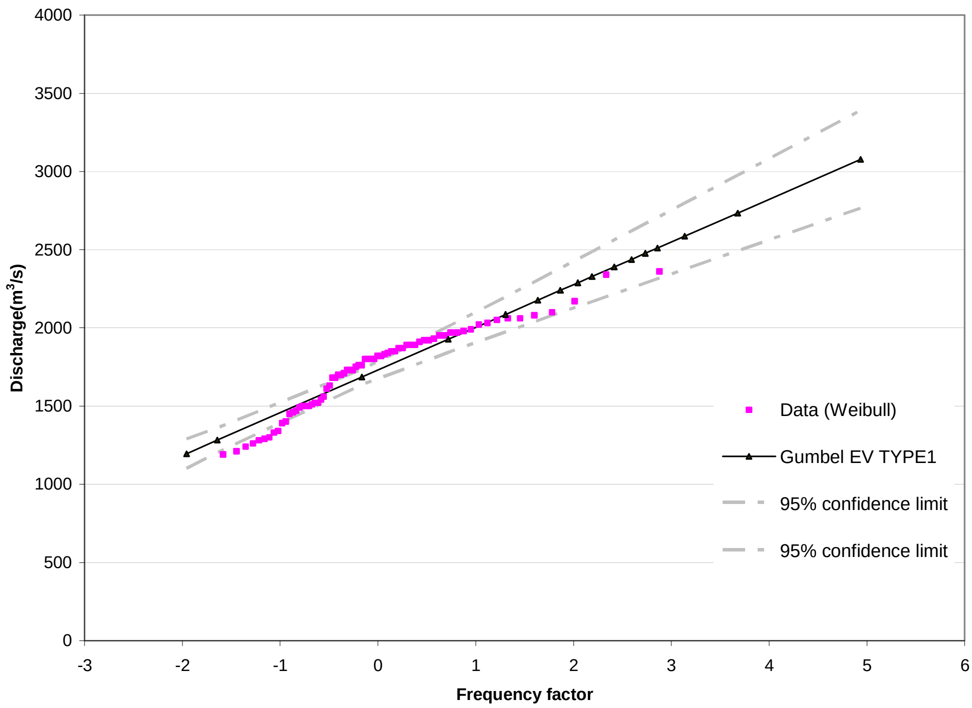


Figure B- 93: Annual maximum flows for the Niger River at Niamey 1929-2006

Table B- 4: Maximum discharge analysis, River Niger at Niamey 1929-2006

F(X)	T (years)	K(T)frequency factor	Q (m3/s)
0.000999	1.001	-1.95703072	1195.31538
0.00990099	1.01	-1.64246093	1281.19176
0.5	2	-0.16427204	1684.73181
0.8	5	0.71945742	1925.98665
0.9	10	1.30456321	2085.71835
0.93333333	15	1.63467496	2175.83763
0.95	20	1.86581074	2238.93683
0.96	25	2.04384594	2287.53978
0.96666667	30	2.1886826	2327.07964
0.975	40	2.41631723	2389.22305
0.98	50	2.5922881	2437.26244
0.98333333	60	2.73576331	2476.43064
0.98571429	70	2.85689446	2509.49899
0.99	100	3.13668064	2585.87957
0.995	200	3.67908679	2733.95443
0.999	1000	4.93552369	3076.95701

APPENDIX C

Table C- 1 lists the key characteristics of the Landsat program. Adapted from [*USGS*, 2006; *USGS and NOAA*, 1984]

Table C- 1: Landsat instrument data

System	Launch (End of service)	Instrument(s)	Altitude (km)	Revisit interval (days)
Landsat 1	23/7/1972 (6/1/1978)	RBV MSS	920	18
Landsat 2	22/1/1975 (25/2/1982)	RBV MSS	920	18
Landsat 3	5/3/1978 (31/3/1983)	RBV MSS	920	18
Landsat 4*	16/7/1982 (15/6/2001)	MSS TM	705	16
Landsat 5	1/3/1984	MSS TM	705	16
Landsat 6	5/10/1993 (5/10/1993)	ETM	705	16
Landsat 7	15/4/1999	ETM+	705	16

*TM data transmission failed in August, 1993

Table C- 2: Landsat MSS resolution

Multi-spectral scanner(MSS)	Landsats 1-3	Landsats 4-5	Wavelength(μm)	Resolution(Meters)
	Band 4	Band 1	0.5 – 0.6	80
	Band 5	Band 2	0.6 – 0.7	80
	Band 6	Band 3	0.7 – 0.8	80
	Band 7	Band 4	0.8 – 1.1	80

Table C- 3 :Landsat TM resolution

Thematic Mapper (TM)	Landsats 4 - 5	Wavelength(μm)	Resolution(meters)
	Band 1	0.45 – 0.52	30
	Band 2	0.52 – 0.60	30
	Band 3	0.63 – 0.69	30
	Band 4	0.76 – 0.90	30
	Band 5	1.55 – 1.75	30
	Band 6	10.40 – 12.50	120*
	Band 7	2.08 – 2.35	30

*The delivered product is resampled to 30 meter pixels.

Table C- 4: Landsat ETM resolution

Enhanced Thematic Mapper (ETM+)	Landsats 7	Wavelength(μm)	Resolution(meters)
	Band 1	0.45 – 0.52	30
	Band 2	0.52 – 0.60	30
	Band 3	0.63 – 0.69	30
	Band 4	0.77 – 0.90	30
	Band 5	1.55 – 1.75	30
	Band 6	10.40 – 12.50	60
	Band 7	2.09 – 2.35	30
	Band 8	0.52 – 0.90	15

Table C- 5: Technical characteristics of the CORONA KH-4A camera system [source: [*USGS*, 1996]]

Period of operation	August 1963 - October 1969
Camera type	Panoramic
Flight altitude	185 km
Focal length	61 cm
Frame format	5.54 cm x 75.69 cm
Film resolution	120 lines/mm
Film width	70 mm
Photo scale of the film	1:305000
Ground coverage	17 km x 232 km
Best ground resolution	2.7 m

CORONA images are captured as parallel strips; the images used for this study are from the CORONA KH-4A camera system.

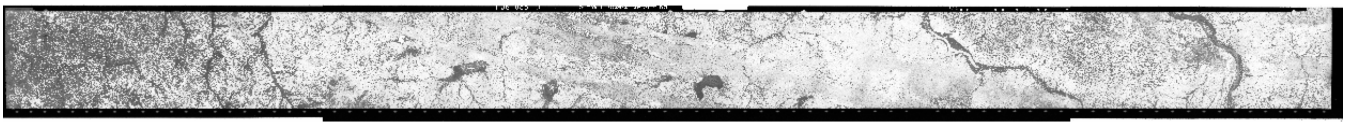


Figure C- 1: Sample image of a re-assembled Corona film strip

Table C- 6: Confusion matrix for the Gorouol basin 1999 using field observed ground truth

Class	Bare soil	Sandy bare soil	Paved/rocky bare soil	Water	Sediment laden water	Shrubs/grass	Tree	Tree, poor state	Total	Prod. Acc.	User Acc.
Bare soil	98.63	0	0	0	0	0	0	0	34.12	98.63	100
Sandy bare soil	1.37	100	0	0	0	0	0	0	6.64	100	92.86
Paved/rocky bare soil	0	0	100	0	0	0	0	0	9	100	100
Water	0	0	0	100	0	0	0	0	25.59	100	100
Sediment laden water	0	0	0	0	87.5	0	0	0	3.32	87.5	100
Shrubs/grass	0	0	0	0	0	100	0	22.22	5.69	100	66.67
Tree	0	0	0	0	12.5	0	88.89	0	8.06	88.89	94.12
Tree, poor state	0	0	0	0	0	0	11.11	77.78	7.58	77.78	87.5
Total	100	100	100	100	100	100	100	100	100		

Table C- 7: Confusion matrix for the Gorouol basin 1992 using field observed ground truth

Class	Bare soil	Sandy bare soil	Paved/rocky bare soil	Water	Sediment laden water	Shrubs/grass	Tree	Tree, poor state	Total	Prod. Acc.	User Acc.
Bare soil	100	53.85	42.86	39.34	0	50	11.11	95.24	63.48	100	54.79
Sandy bare soil	0	46.15	0	0	0	0	0	0	2.61	46.15	100
Paved/rocky bare soil	0	0	4.76	0	0	0	0	0	0.43	4.76	100
Water	0	0	0	29.51	0	0	0	0	7.83	29.51	100
Sediment laden water	0	0	0	0	62.5	0	0	0	2.17	62.5	100
Shrubs/grass	0	0	4.76	11.48	0	37.5	5.56	4.76	5.65	37.5	23.08
Tree	0	0	4.76	0	25	12.5	83.33	0	8.26	83.33	78.95
Tree, poor state	0	0	42.86	19.67	12.5	0	0	0	9.57	0	0
Total	100	100	100	100	100	100	100	100	100		

Table C- 8: Confusion matrix for the Gorouol basin 1984 using field observed ground truth

Class	Bare soil	Sandy bare soil	Paved/rocky bare soil	Water	Sediment laden water	Shrubs/grass	Tree	Tree, poor state	Total	Prod. Acc.	User Acc.
Bare soil	15.38	0	4.55	46.15	62.5	62.5	38.89	0	26.09	15.38	20
Sandy bare soil	6.41	92.31	45.45	0	0	0	0	11.11	12.61	92.31	41.38
Paved/rocky bare soil	0	0	0	0	0	0	0	0	0	0	0
Water	0	0	0	0	0	0	0	0	0	0	0
Sediment laden water	3.85	0	36.36	24.62	0	37.5	0	0	13.04	24.62	53.33
Shrubs/grass	74.36	7.69	4.55	23.08	37.5	0	44.44	0	37.39	0	0
Tree	0	0	0	1.54	0	0	11.11	66.67	6.52	11.11	13.33
Tree, poor state	0	0	9.09	4.62	0	0	5.56	22.22	4.35	22.22	40
Total	100	100	100	100	100	100	100	100	100		

Table C- 9: Confusion matrix for the Gorouol basin 1979 using 1959 map ground truth

Class	Bare soil	Water	Tree	Tree, poor state	Total	Prod. Acc.	User Acc.
Bare soil	100	0	25.27	0	52.2	100	91.93
Water	0	100	0	0	19.6	100	100
Tree	0	0	74.73	72.09	23.81	74.73	52.31
Tree, poor state	0	0	0	27.91	4.4	27.91	100
Total	100	100	100	100	100		

Table C- 10: Confusion matrix for the Sirba basin 1999 using field observed ground truth

Class	Bare soil	Sandy bare soil	Paved/rocky bare soil	Water	Sediment laden water	Shrubs/grass	Tree	Tree, poor state	Total	Prod. Acc.	User Acc.
Bare soil	87.5	0.58	0	0	0	0	0	0	2.73	87.5	87.5
Sandy bare soil	0	98.83	0	0	0	0	0	0	57.68	98.83	100
Paved/rocky bare soil	0	0	100	0	0	0	0	0	1.37	100	100
Water	0	0	0	100	0	0	0	0	3.75	100	100
Sediment laden water	12.5	0	0	0	100	0	0	0	3.75	100	90.91
Shrubs/grass	0	0	0	0	0	66.67	0	0	0.68	66.67	100
Tree	0	0.58	0	0	0	33.33	100	7.84	13.99	100	85.37
Tree, poor state	0	0	0	0	0	0	0	92.16	16.04	92.16	100
Total	100	100	100	100	100	100	100	100	100		

Table C- 11: Confusion matrix for the Sirba basin 1989 using field observed ground truth

Class	Bare soil	Sandy bare soil	Paved/rocky bare soil	Water	Sediment laden water	Shrubs/grass	Tree	Tree, poor state	Total	Prod. Acc.	User Acc.
Bare soil	62.5	16.76	75	0	0	100	97.92	0	27.85	62.5	5.68
Sandy bare soil	0	81.01	25	0	0	0	0	0	46.2	81.01	99.32
Paved/rocky bare soil	25	1.68	0	0	20	0	2.08	1.89	2.85	0	0
Water	0	0	0	90.91	10	0	0	0	3.48	90.91	90.91
Sediment laden water	12.5	0	0	9.09	50	0	0	0	2.22	50	71.43
Shrubs/grass	0	0	0	0	0	0	0	1.89	0.32	0	0
Tree	0	0	0	0	0	0	0	20.75	3.48	0	0
Tree, poor state	0	0.56	0	0	20	0	0	75.47	13.61	75.47	93.02
Total	100	100	100	100	100	100	100	100	100		

Table C- 12: Confusion matrix for the Sirba basin 1984 using 1980 map ground truth

Class	Bare soil	Paved/rocky bare soil	Water	Shrubs/grass	Tree	Tree, poor state	Total	Prod. Acc.	User Acc.
Bare soil	100	0	0	22.22	0	0	11.16	100	91.55
Paved/rocky bare soil	0	100	0	0	0	11.54	10.53	100	95.52
Water	0	0	100	0	0	0	67.3	100	100
Shrubs/grass	0	0	0	77.78	0	0	3.3	77.78	100
Tree	0	0	0	0	50	50	4.09	50	50
Tree, poor state	0	0	0	0	50	38.46	3.62	38.46	43.48
Total	100	100	100	100	100	100	100		

Table C- 13: Confusion matrix for the Sirba basin 1975 using 1980 map ground truth

Class	Bare soil	Paved/rocky bare soil	Water	Shrubs/grass	Tree	Tree, poor state	Total	Prod. Acc.	User Acc.
Bare soil	0	0	0	0	0	0	0	0	0
Paved/rocky bare soil	0	0	0	0	0	0	0	0	0
Water	0	0	100	0	0	0	65.84	100	100
Shrubs/grass	100	100	0	100	25	0	25.47	100	19.51
Tree	0	0	0	0	50	75	6.21	50	40
Tree, poor state	0	0	0	0	25	25	2.48	25	50
Total	100	100	100	100	100	100	100		

Table C- 14: Confusion matrix for the Mékrou basin 2000 using 1959 map ground truth

Class	Bare soil	Water	Tree	Total	Prod. Acc.	User Acc.
Bare soil	0	0	7.12	6.79	0	0
Water	0	33.33	0	1.36	33.33	100
Tree	100	66.67	92.88	91.85	92.88	96.49
Total	100	100	100	100		

Table C- 15: Confusion matrix for the Mékrou basin 1973 using 1959 map ground truth

Class	Bare soil	Water	Tree	Total	Prod. Acc.	User Acc.
Bare soil	100	63.64	7.09	20.59	100	51.43
Water	0	36.36	0	2.35	36.36	100
Tree	0	0	92.91	77.06	92.91	100
Total	100	100	100	100		

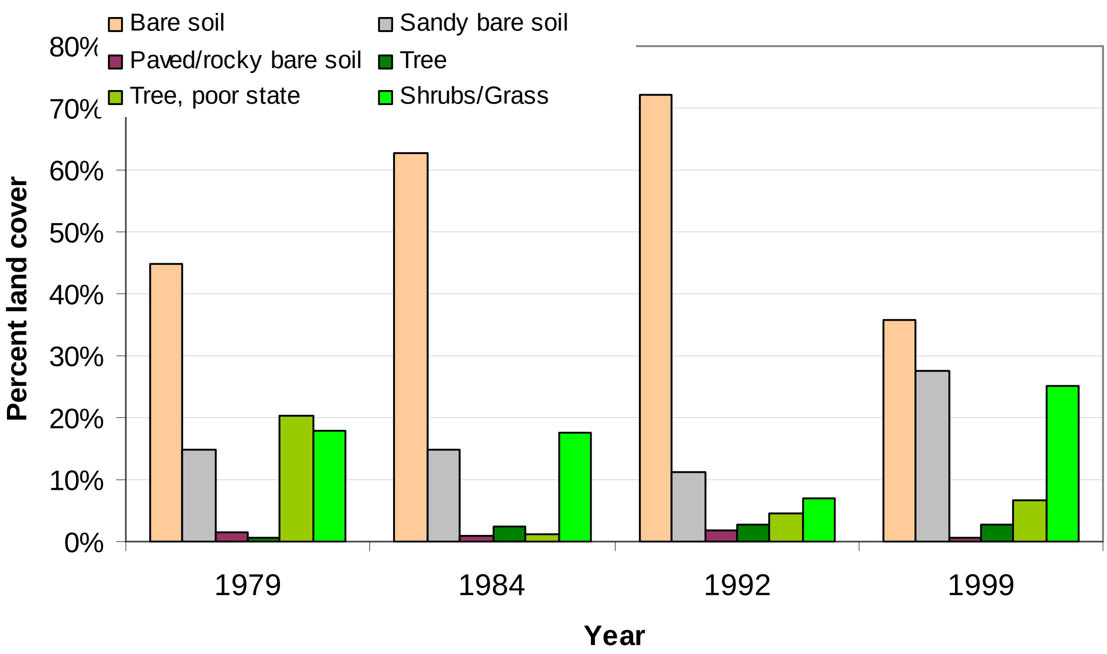


Figure C- 2: Percentage land cover Gorouol 1979-1999

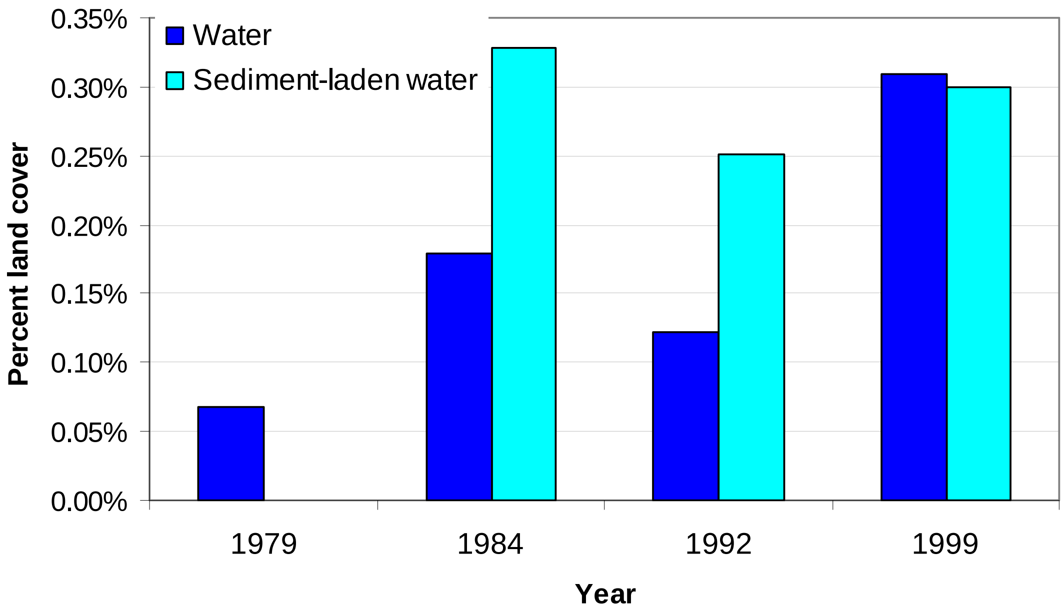


Figure C- 3: Water/sediment-laden water surface area in the Gorouol basin (1979-1999)

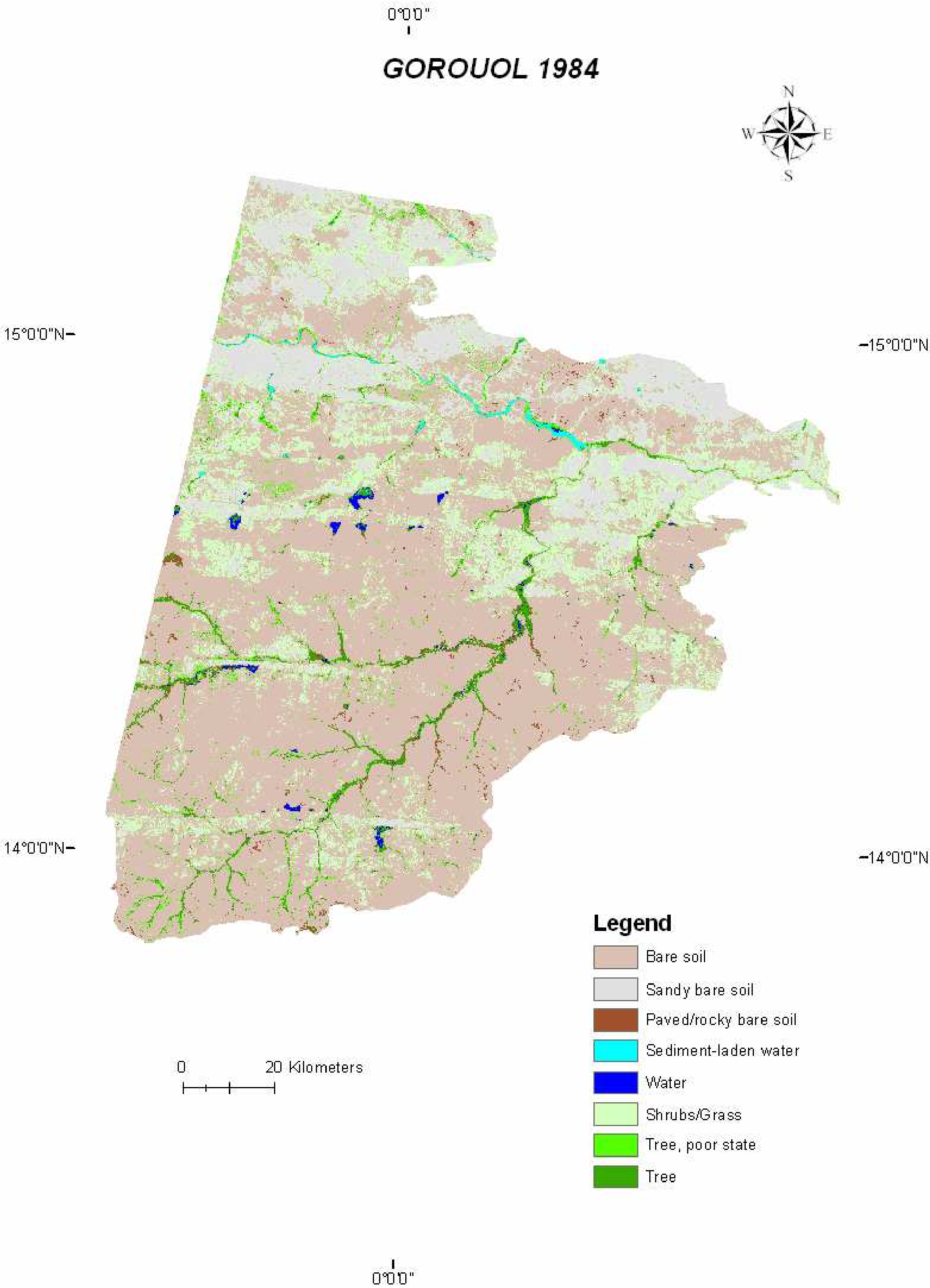


Figure C- 4: Gorouol basin land cover in 1984 (14888 km²)

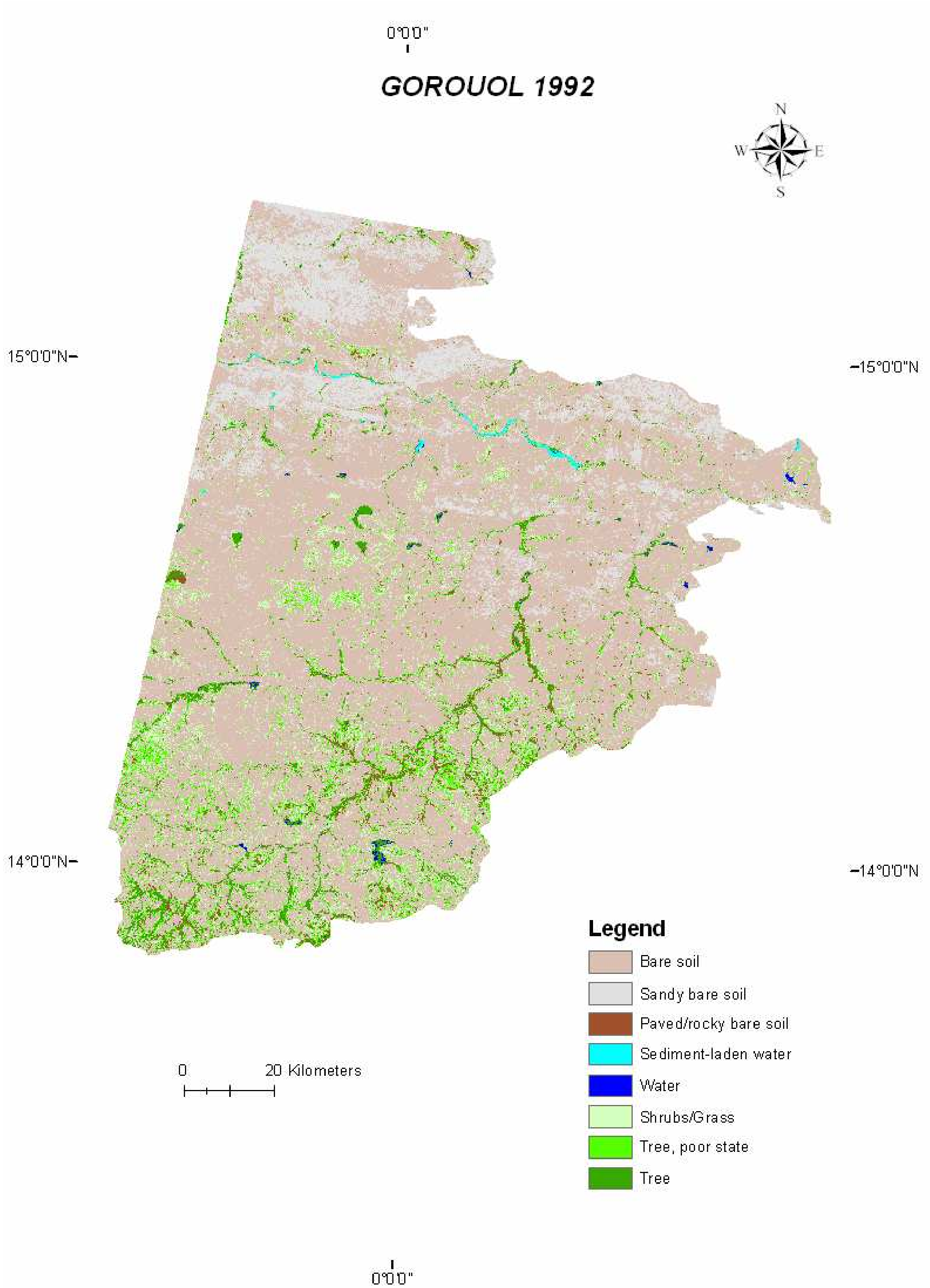


Figure C- 5: Gorouol basin land cover in 1992 (14888 km²)

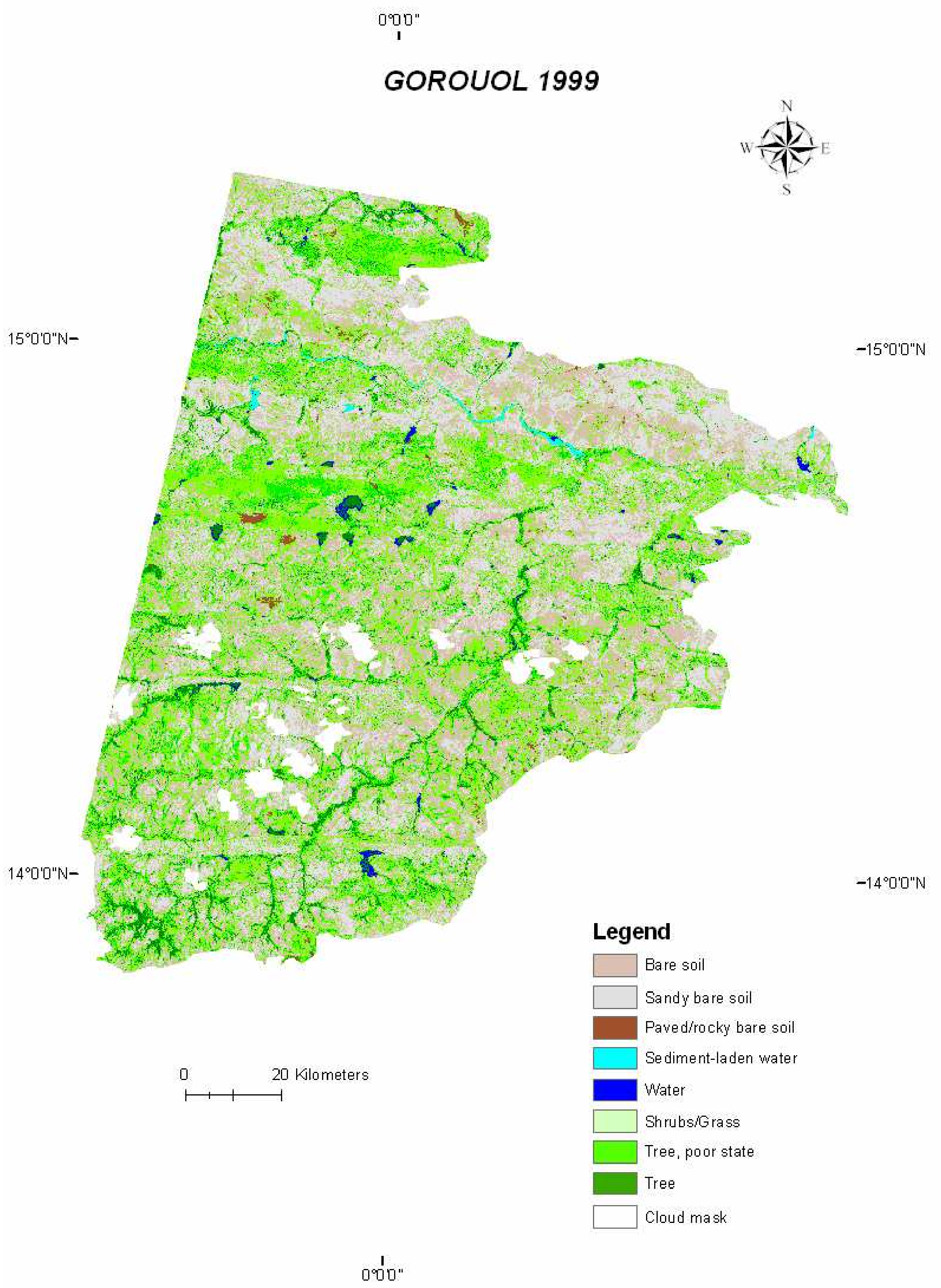


Figure C- 6: Gorouol basin land cover in 1999 (14888 km²)

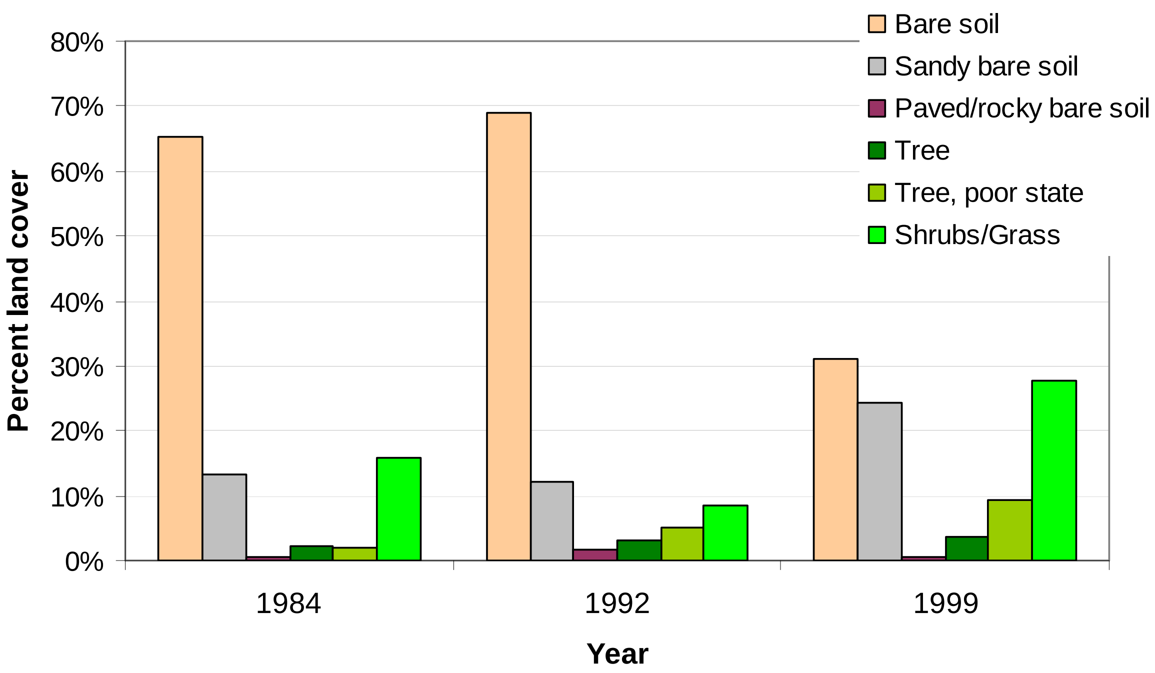


Figure C- 7: Percentage land cover Gorouol 1984-1999

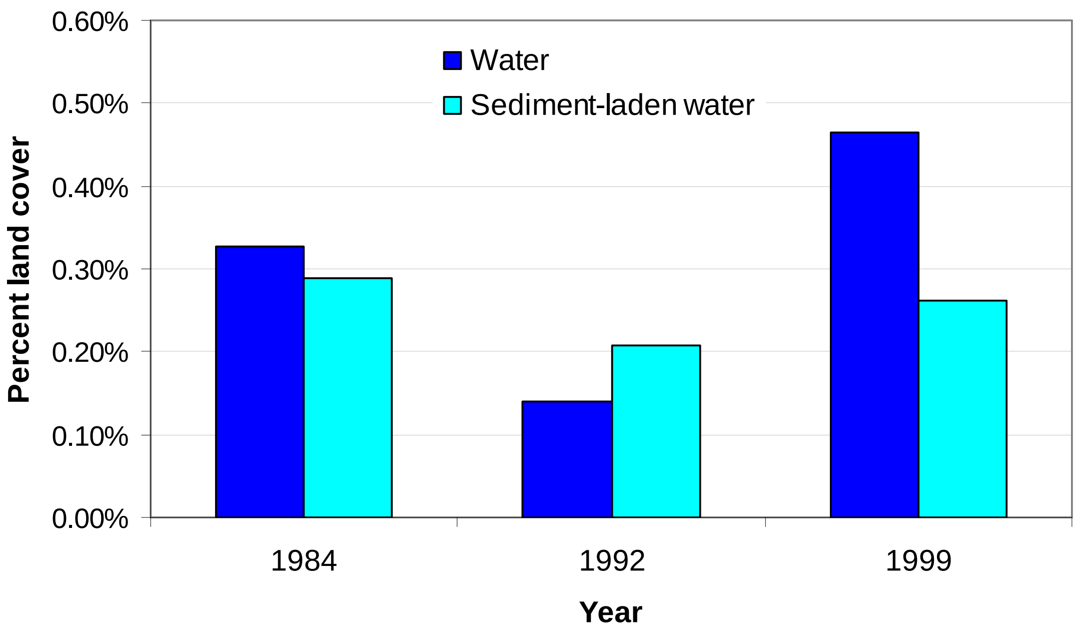


Figure C- 8: Water/sediment-laden water surface area in the Gorouol basin (1984-1999)

Table C- 16: Gorouol between 1984 and 1999 Area (14888 km²)

Class	1984	1992	1999
Water	0.33	0.14	0.47
Sediment-laden water	0.29	0.21	0.26
Bare soil	65.38	69.04	31.14
Bare sandy soil	13.23	12.12	24.30
Bare paved/rocky soil	0.65	1.78	0.55
Tree	2.39	3.16	3.76
Tree (poor state)	1.98	5.09	9.28
Shrubs/Grass	15.76	8.46	27.75

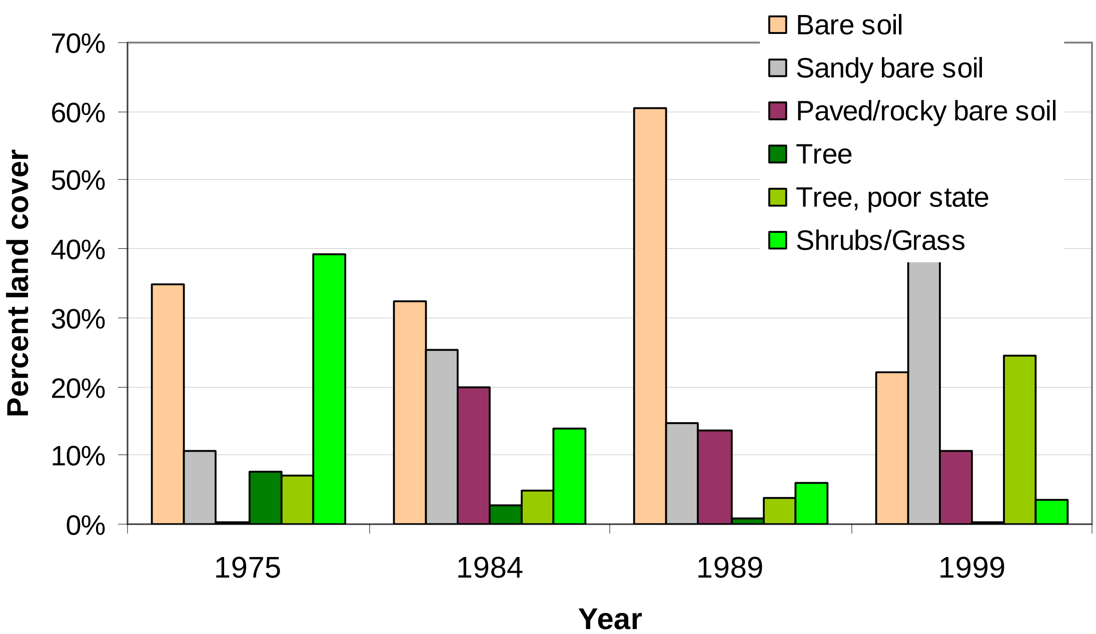


Figure C- 9: Percentage land cover Sirba 1975-1999

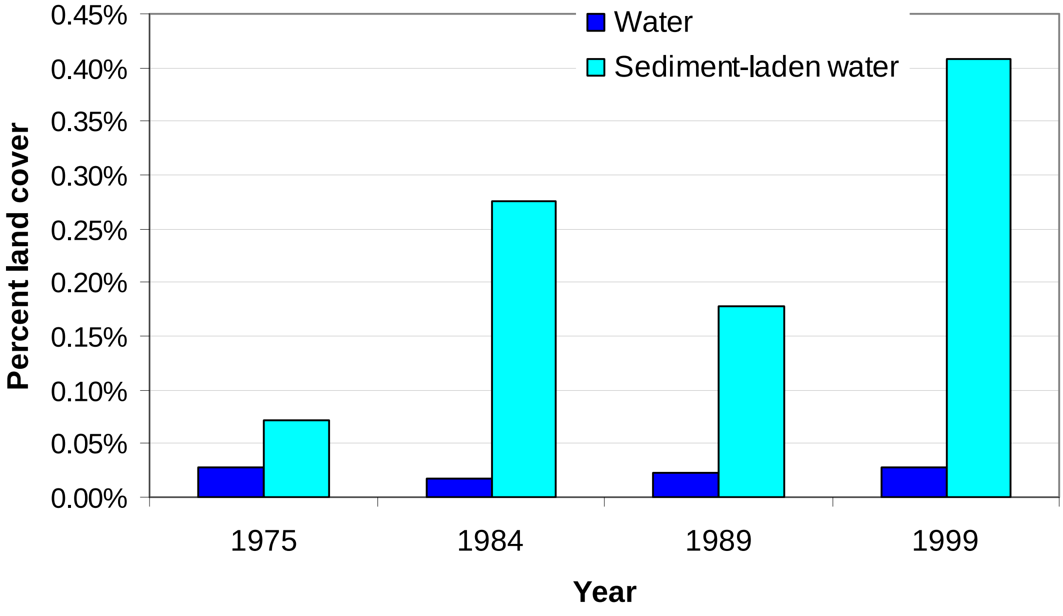


Figure C- 10 Water/sediment-laden water surface area in the Sirba basin (1975-1999)

b) Comparison of the land cover in the Sirba basin for 1984, 1989 and 1999 (Area: 5104 km²)

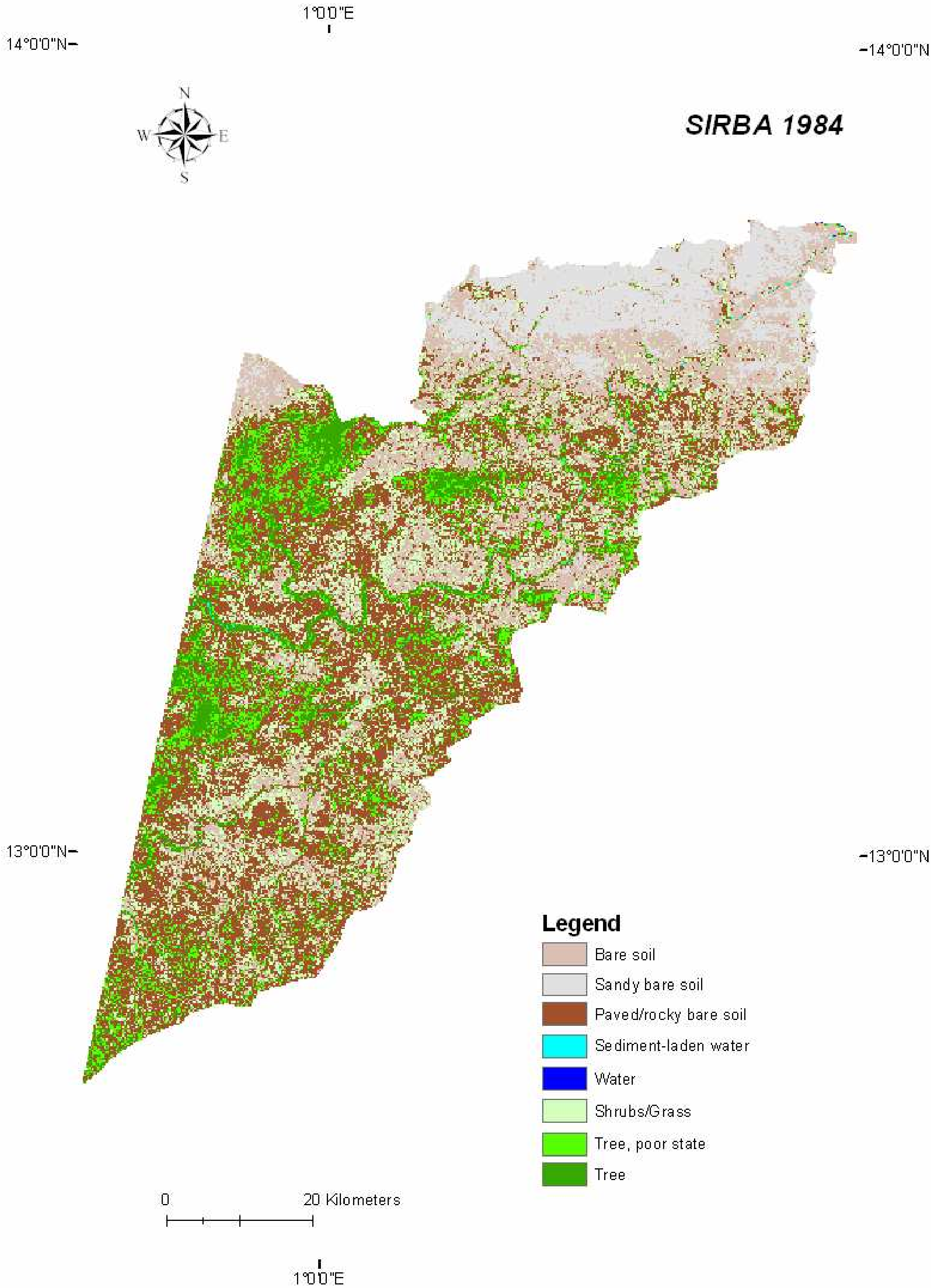


Figure C- 11: Sirba basin land cover in 1984 (5104 km²)

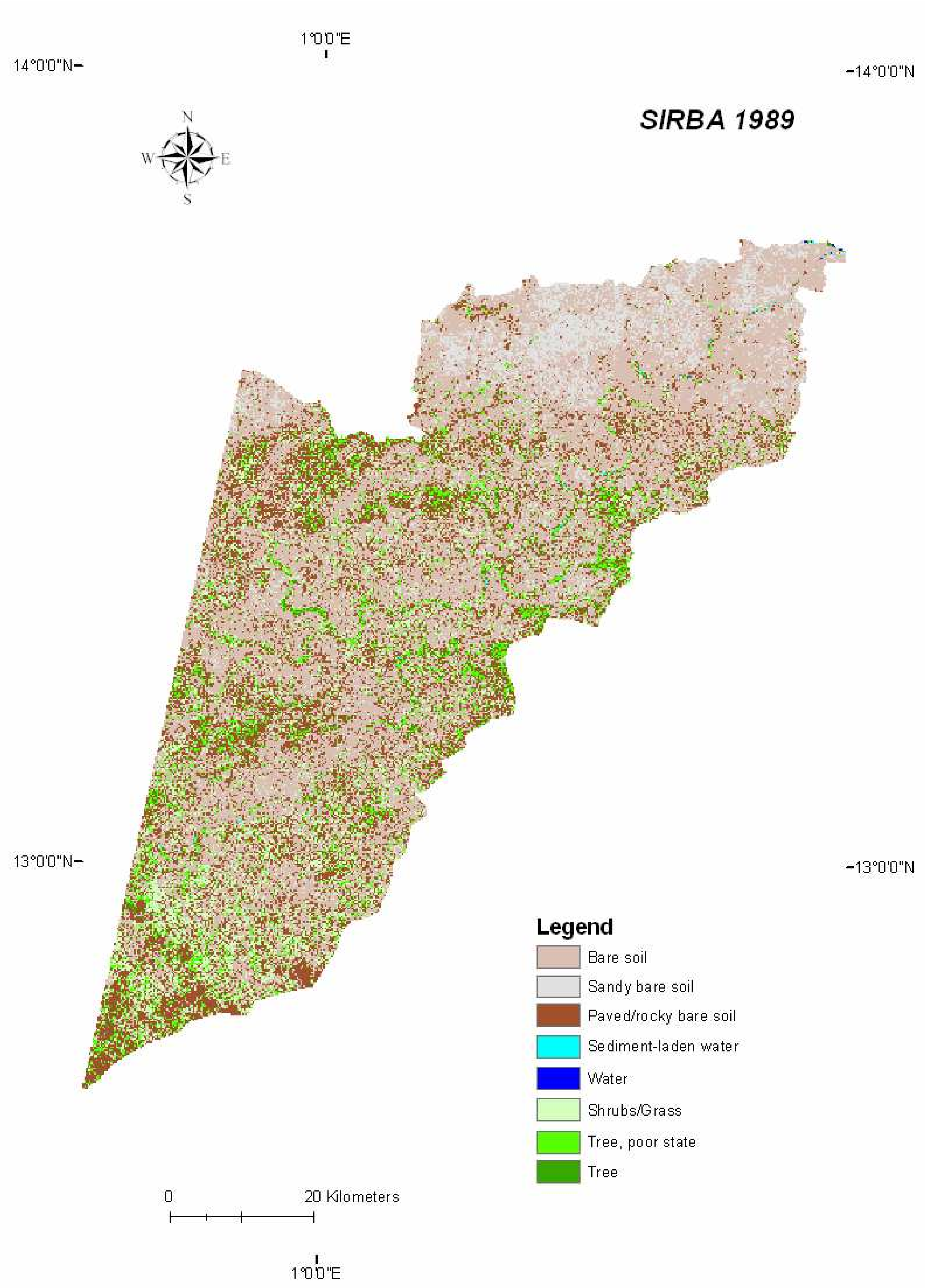


Figure C- 12: Sirba basin land cover in 1989 (5104 km²)

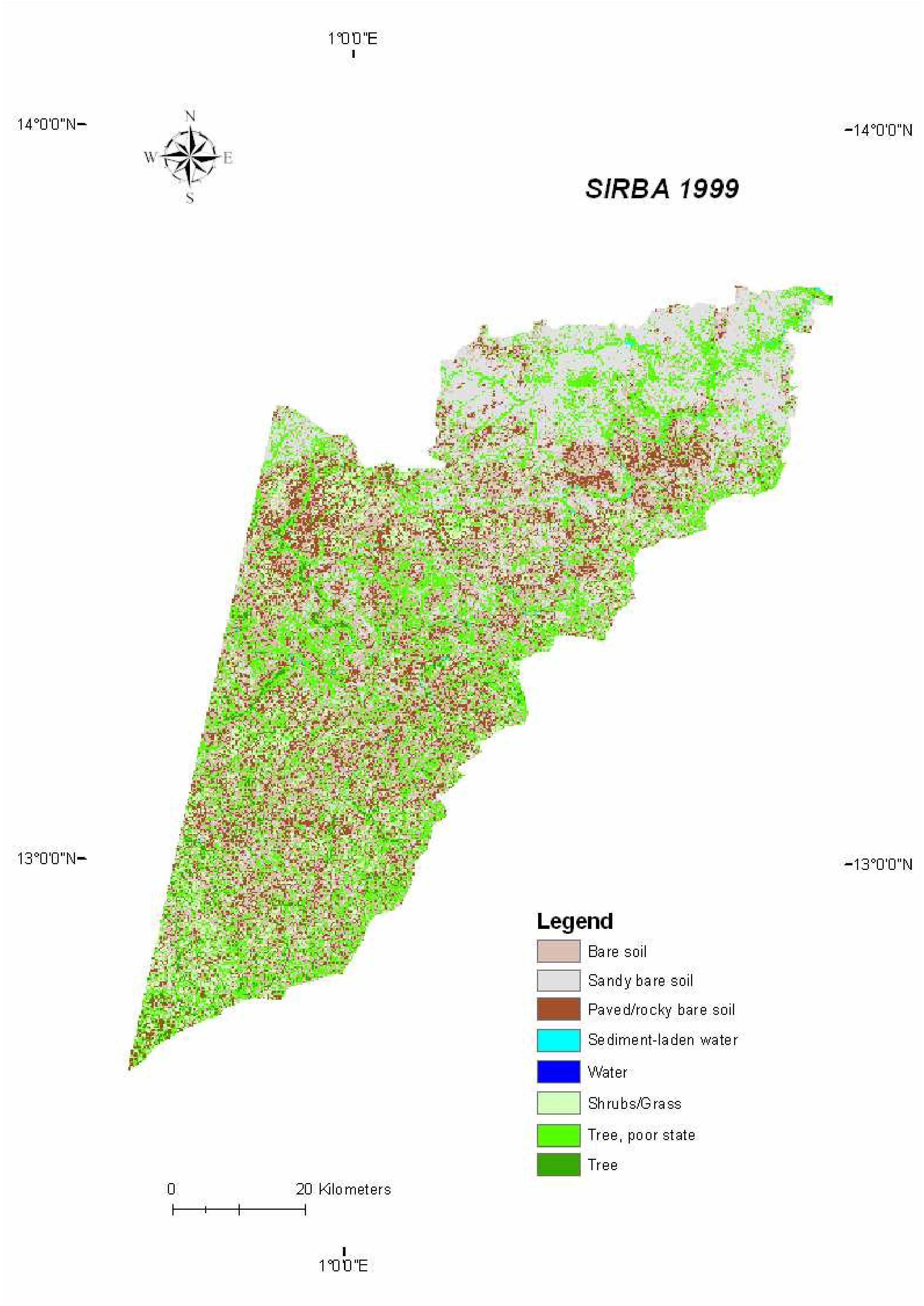


Figure C- 13: Sirba basin land cover in 1999 (5104 km²)

Table C- 17: Sirba percentage land cover 1984 - 1999 Area (5104 km²)

Class	1984	1989	1999
Water	0.01	0.01	0.01
Sediment-laden water	0.13	0.06	0.19
Bare soil	19.25	48.37	28.22
Bare sandy soil	10.00	7.67	19.74
Bare paved/rocky soil	36.51	23.59	16.56
Tree	6.44	0.95	2.15
Tree (poor state)	10.02	6.63	23.70
Shrubs/Grass	17.64	12.73	9.43

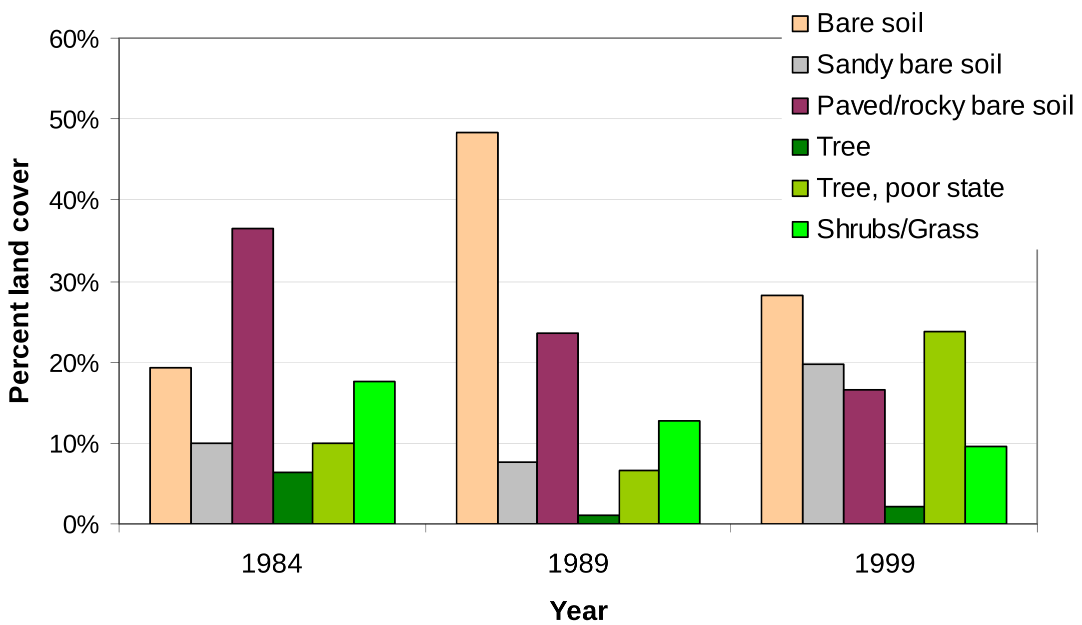


Figure C- 14: Percentage land cover Sirba 1984-1999

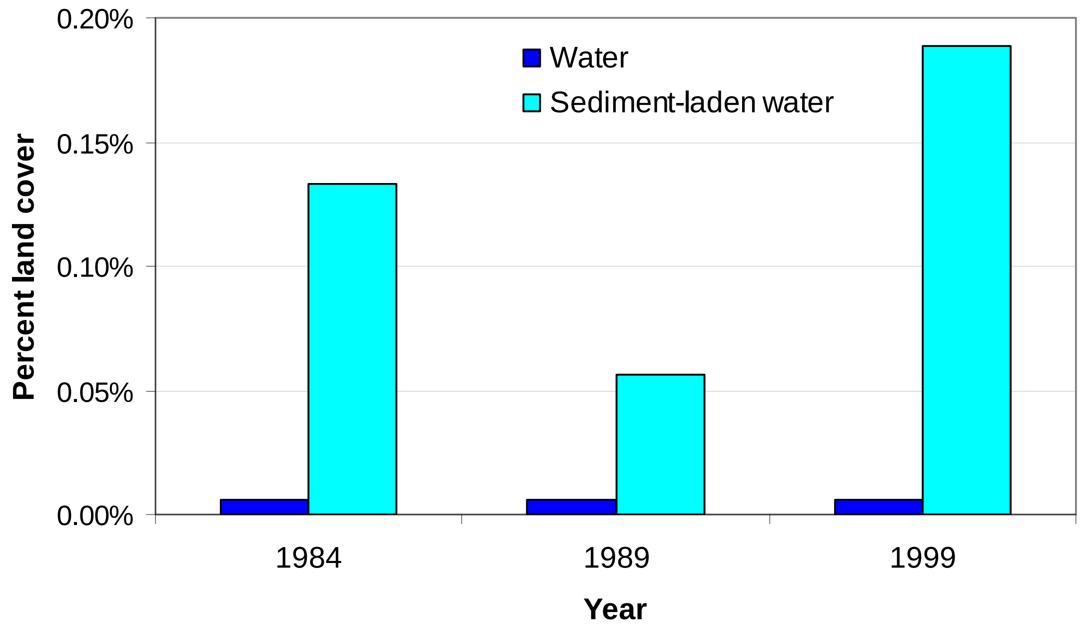


Figure C- 15: Water/sediment-laden water surface area in the Sirba basin (1984-1999)

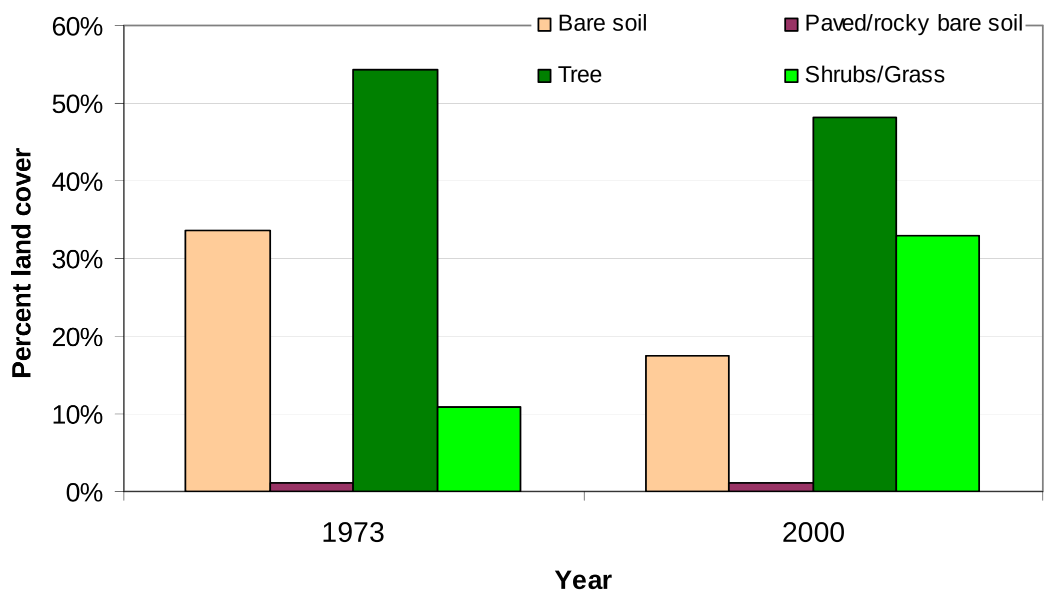


Figure C- 16: Percentage land cover Mekrou 1973-1999 (7690 km²)

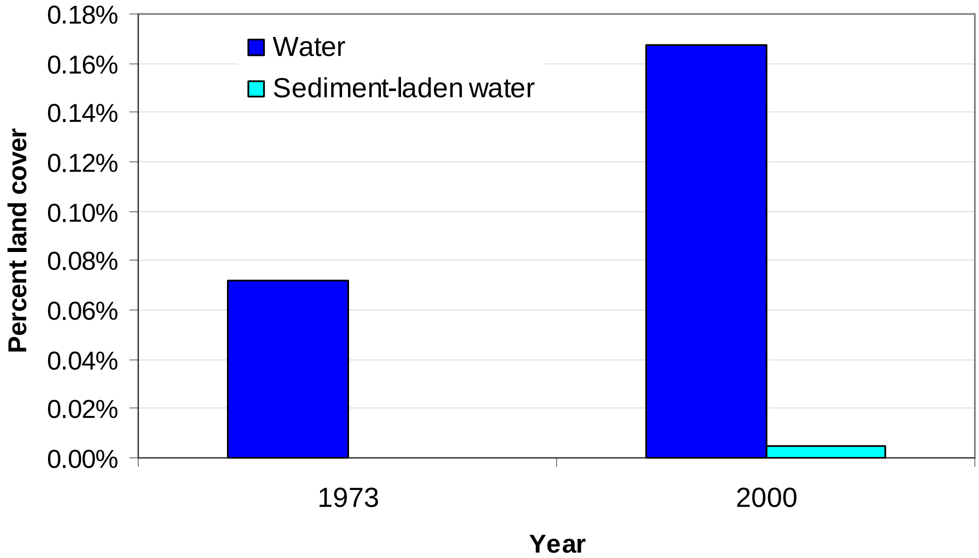


Figure C- 17: Water/sediment-laden water surface area in the Mékrou basin (1973-2000) (7690 km²)

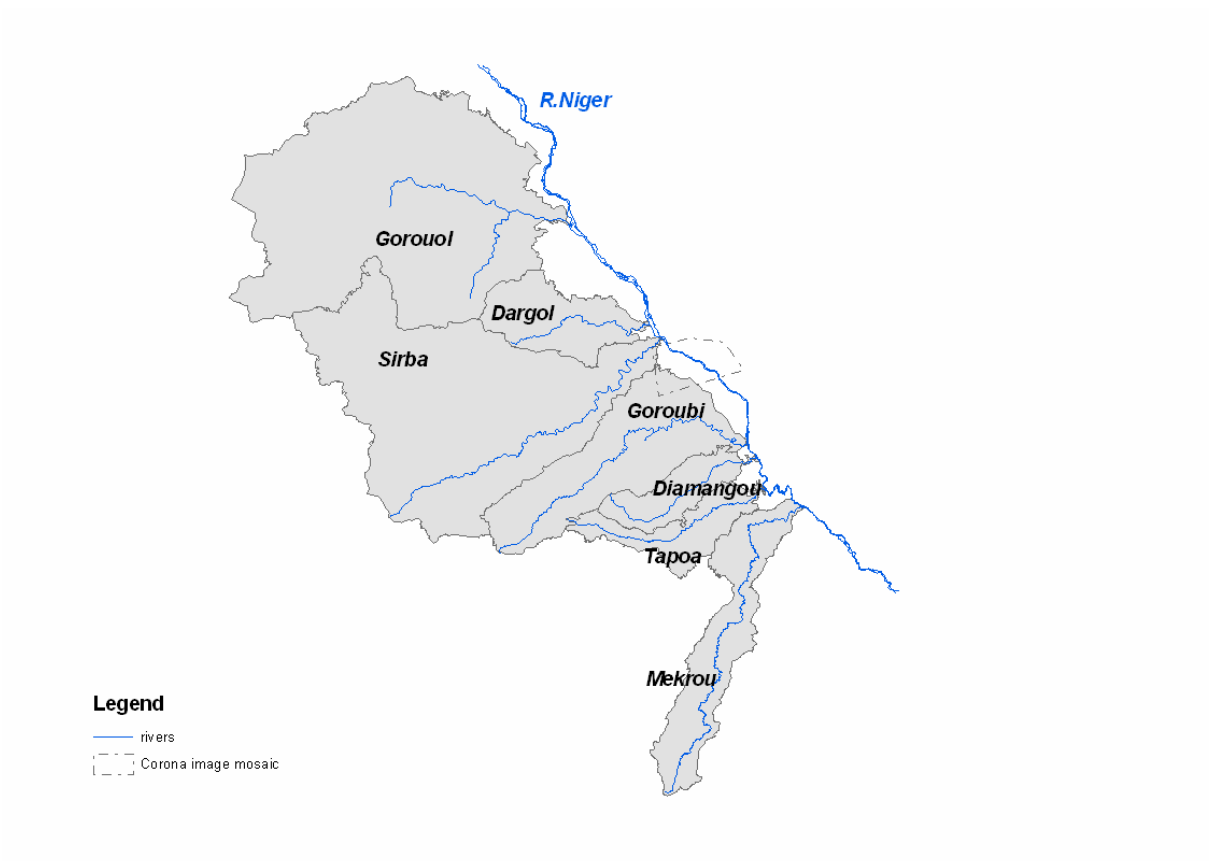


Figure C- 18: The middle Niger basin showing 1965 Corona image mosaic (2840km²)

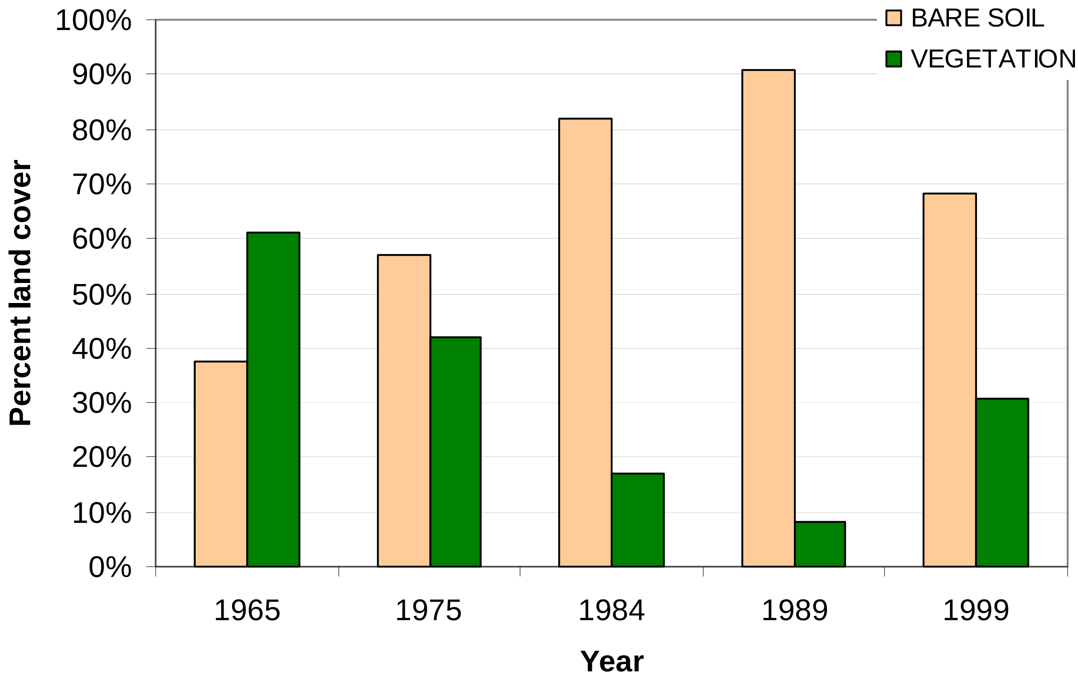


Figure C- 19 :Percentage land cover of the area covered by the Corona mosaic 1965-1999 (2840 km²)

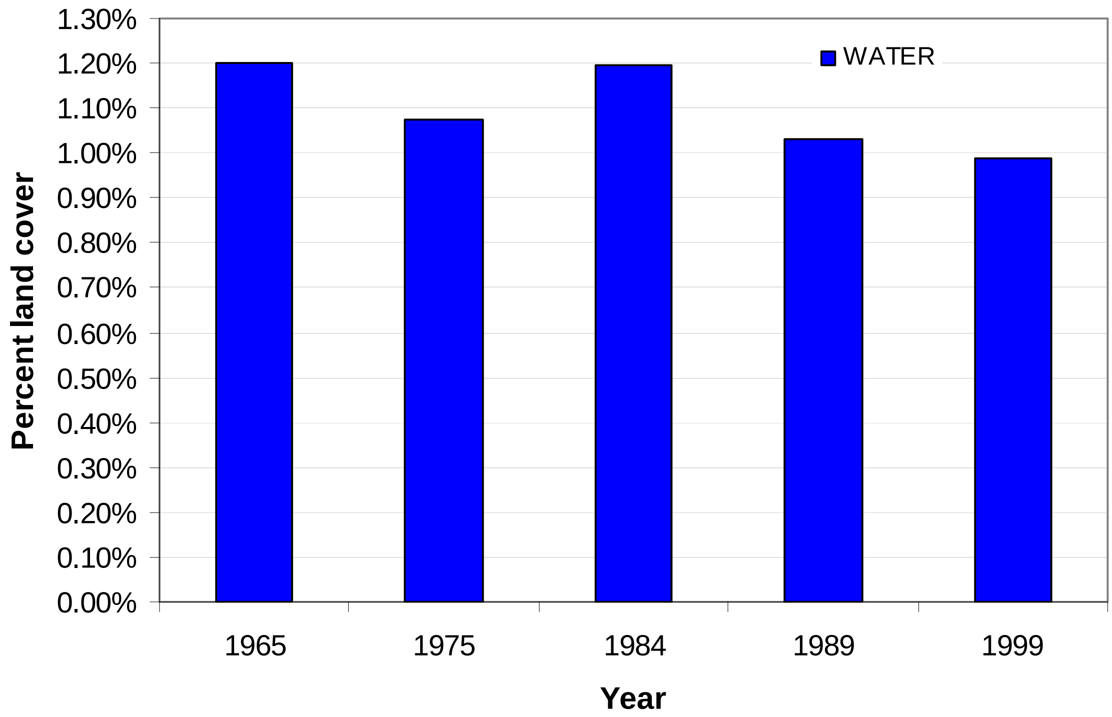


Figure C- 20 Water surface area in the Corona mosaic area 1965-1999 (2840 km²)

Table C- 18: Percentage land cover change of the 1965 Corona mosaic area (2840 km²)

Class	**1965**	**1975**	**1984**	**1989**	**1999**
Water	1.20	1.07	1.19	1.03	0.99
Bare soil	12.51	36.99	34.12	54.89	15.32
Bare sandy soil	13.46	8.26	32.49	24.94	46.17
Bare paved/rocky soil	11.73	11.74	15.27	10.86	6.67
Tree	27.49	6.19	1.13	1.20	1.03
Tree (poor state)	22.21	4.22	2.27	2.19	28.06
Shrubs/Grass	11.41	31.54	13.52	4.89	1.77

APPENDIX D

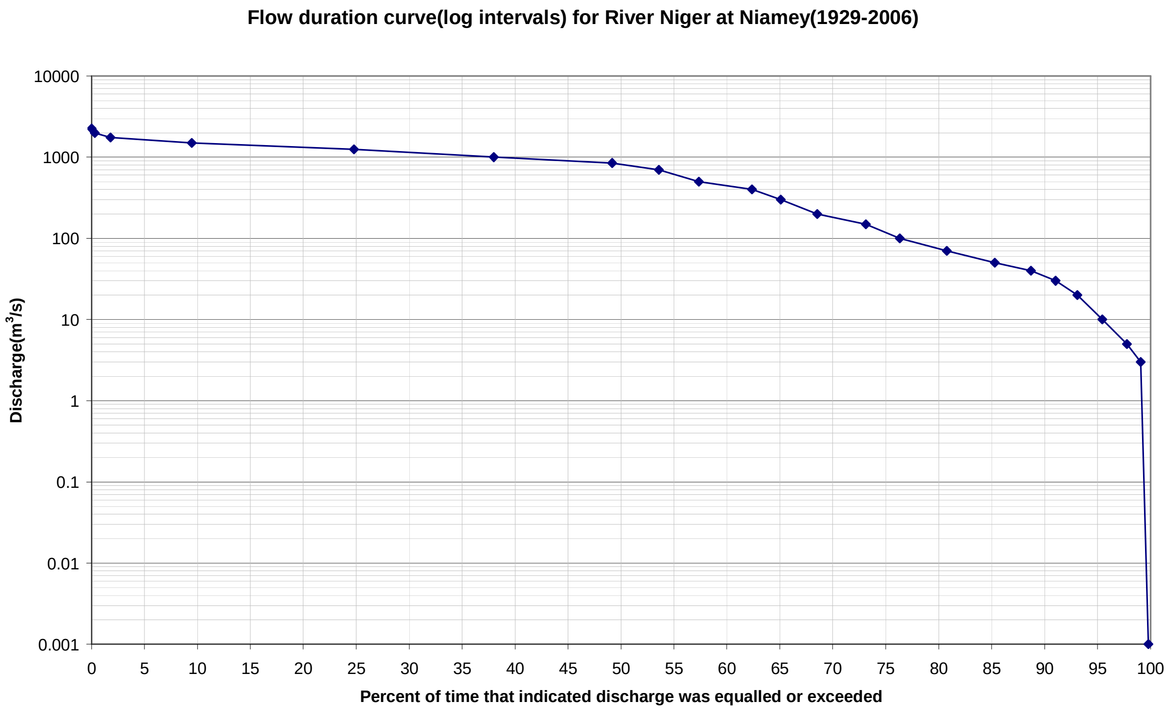


Figure D- 1: Flow duration curve, Niger at Niamey (1929-2006)

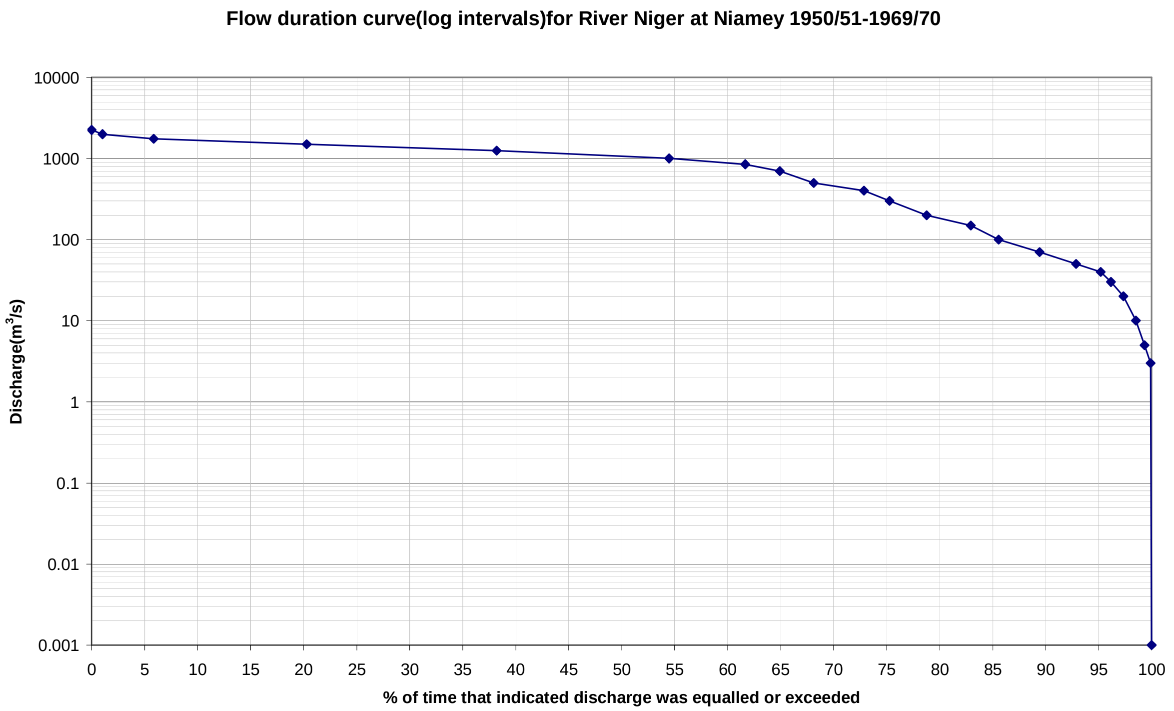


Figure D- 2 :Flow duration curve, Niger at Niamey (Wet spell)

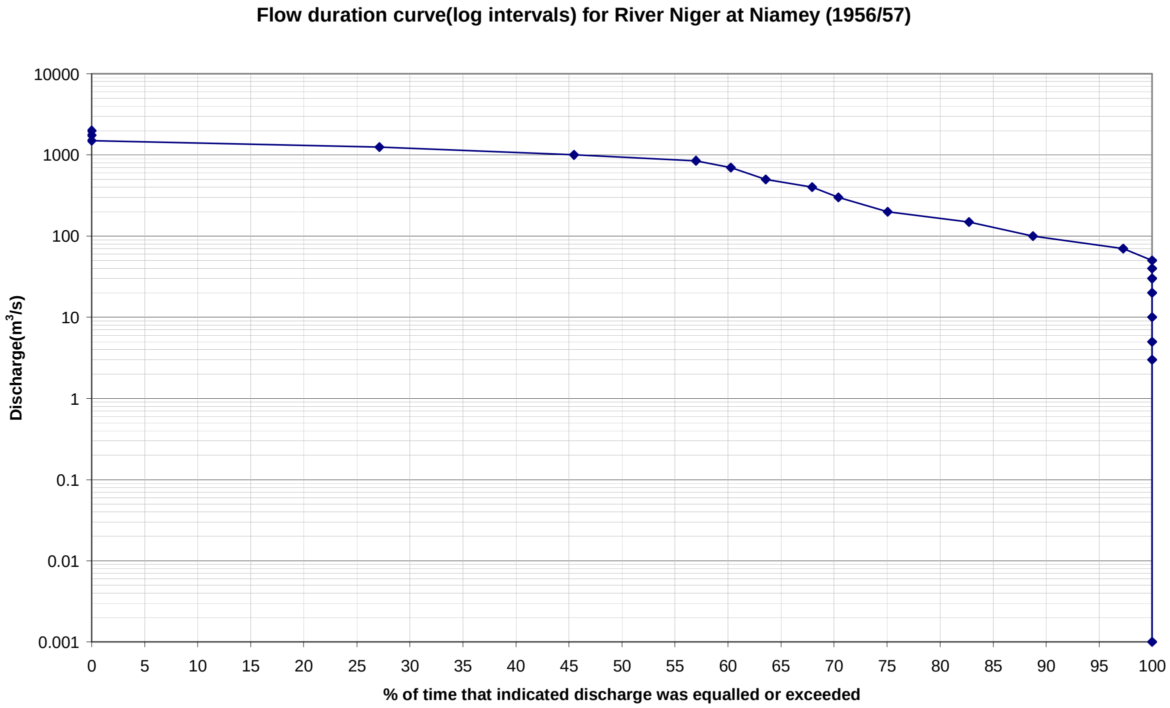


Figure D- 3: Flow duration curve, Niger at Niamey (Wettest year)

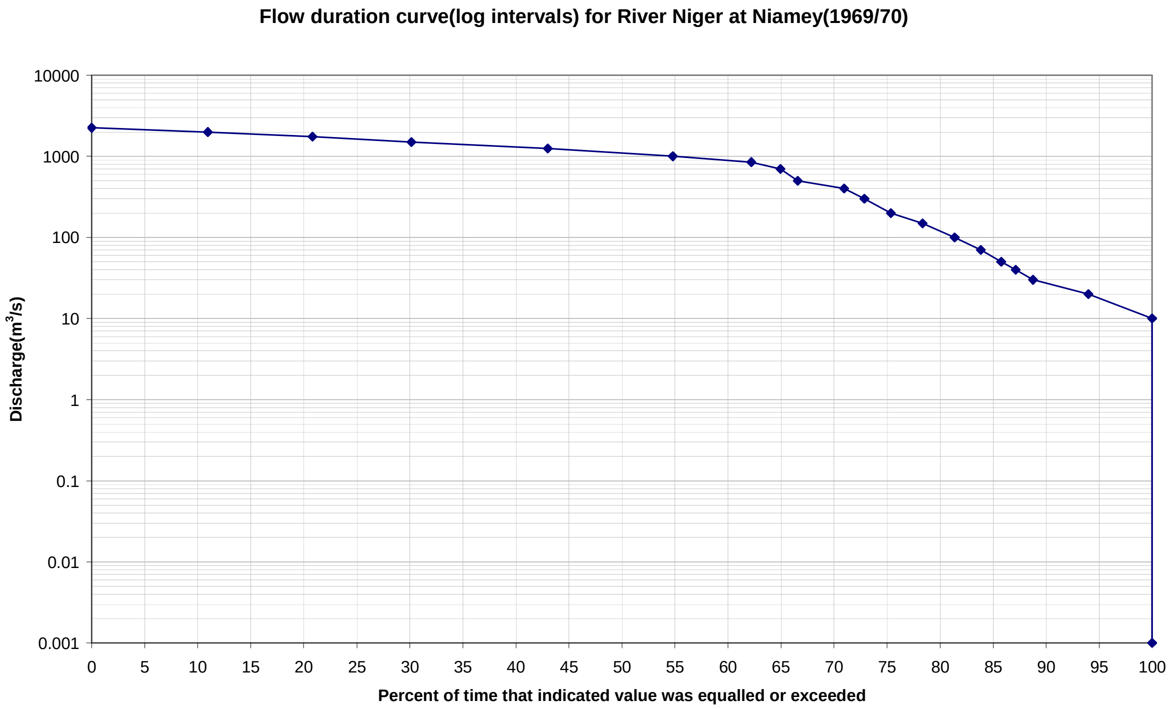


Figure D- 4: Flow duration curve, Niger at Niamey (Maximum daily discharge)

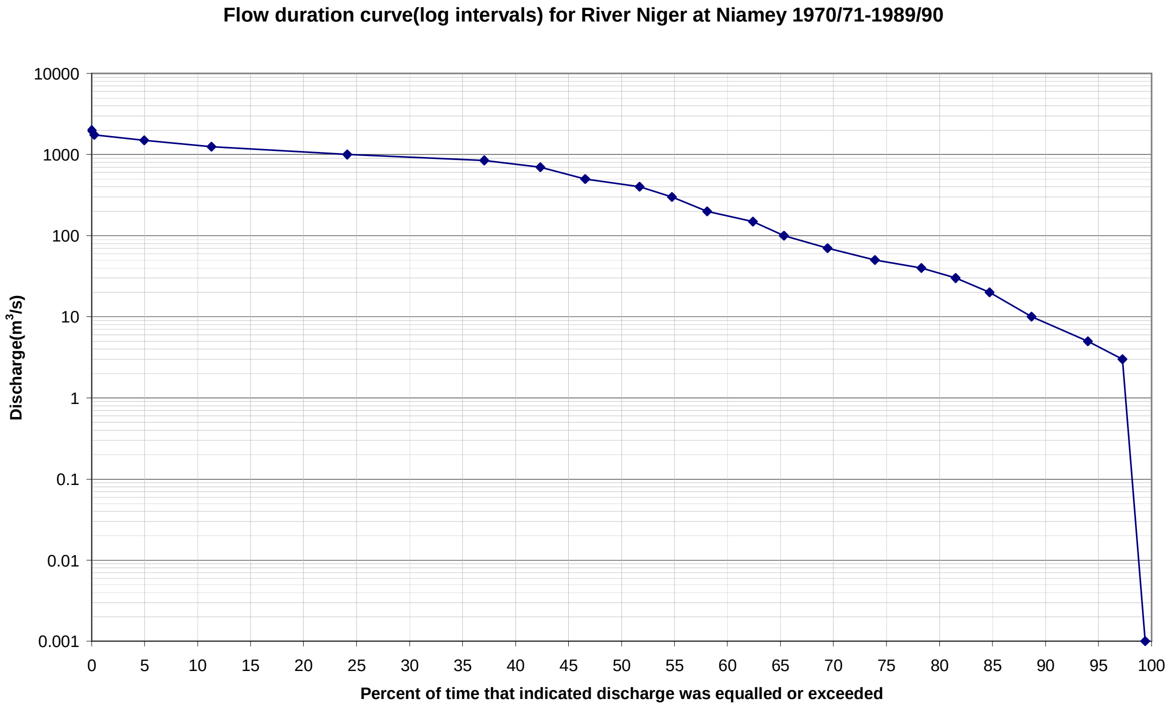


Figure D- 5: Flow duration curve, Niger at Niamey (Dry spell)

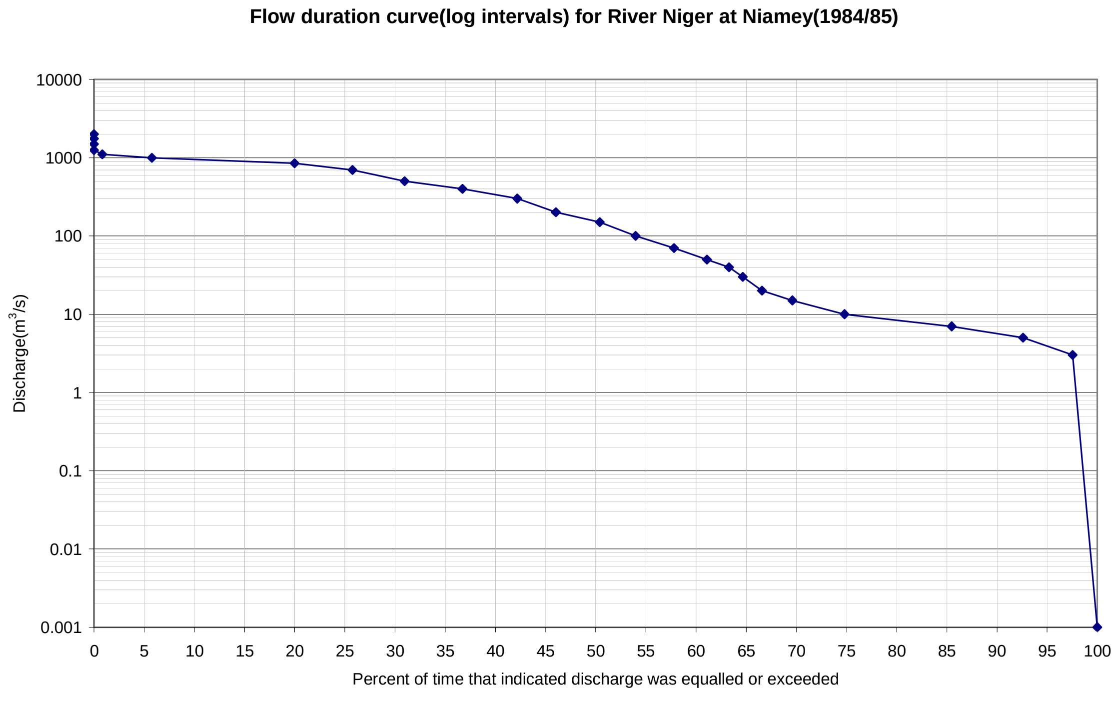


Figure D- 6: Flow duration curve, Niger at Niamey (Driest year)

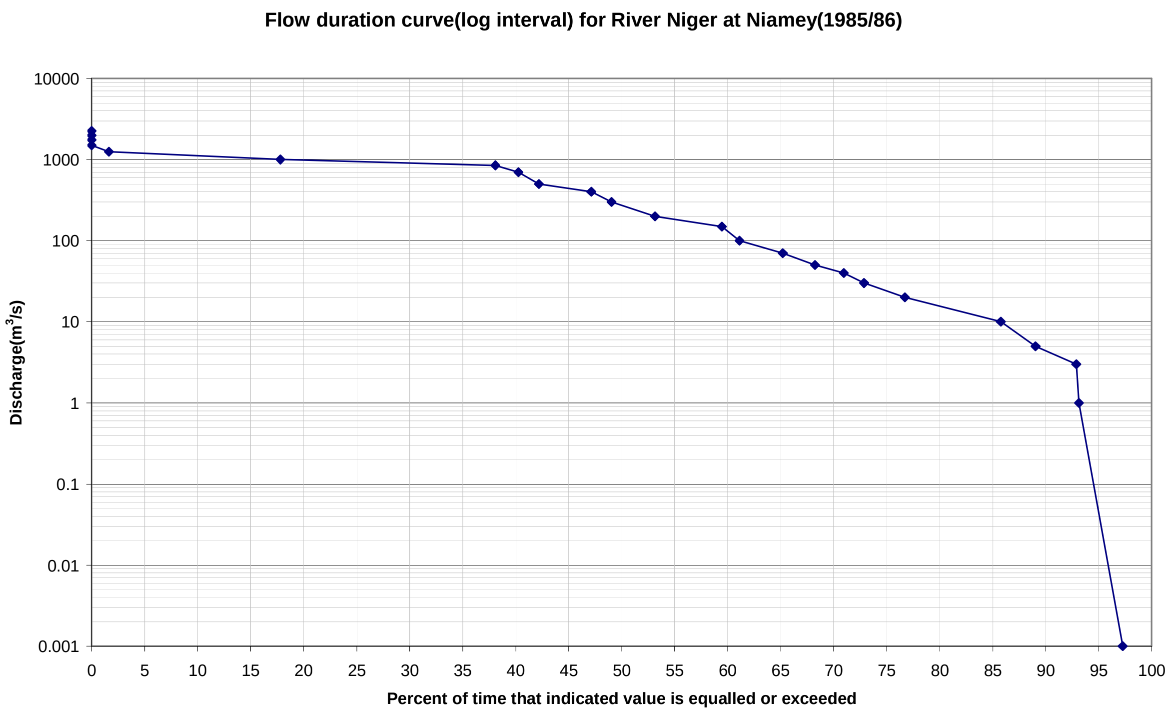


Figure D- 7: Flow duration curve, Niger at Niamey (Minimum daily discharge)

Table D- 1: Monthly Pan Evaporation (mm) from FAO web LocClim estimator

	Kandadji	Diamballa	Tillabery	Kourani	Farie-haoussa	Garbe-kourou	Niamey
January	214	225	226	224	221	221	220
February	222	231	232	231	230	230	234
March	274	281	282	280	275	274	272
April	271	278	279	277	271	270	266
May	281	282	282	281	277	276	275
June	243	240	240	239	233	233	225
July	218	214	214	213	207	207	199
August	183	180	180	178	173	173	165
September	189	191	192	190	182	182	172
October	221	228	229	226	218	217	208
November	214	226	228	225	218	218	213
December	215	228	229	227	222	221	219
Total	2745	2804	2813	2791	2727	2722	2668

Mean annual evaporation between Kandadji and Niamey = 2752.86 mm

Correction factor for class A pan rates =0.75

2752.86 x 0.75 = 2064.64 mm =0.002064 km

Estimated river surface area between Kandadji and Niamey= 370 km²

Evaporation losses = 0.002064/370 = $7.64*10^8$ m^3

Extended Résumé (en français)

Introduction: L'ensablement du fleuve Niger, mythe ou réalité?

1. Contexte

Durant ces dernières décennies, la végétation naturellement éparse du Sahel, région semi-aride en Afrique de l'Ouest, a été sérieusement affectée par une réduction de 25 à 30 pour cent des précipitations, couplée à une pression croissante du bétail et des hommes du fait du surpâturage et de l'augmentation des besoins en bois de chauffe [*M-F Courel*, 1985; *L Descroix*, 2003]. Il a été observé que la diminution des précipitations a eu un effet amplifié sur les débits du fleuve Niger.

Pendant la même période, du fait de l'augmentation des surfaces de sols nus, les sédiments ont été plus facilement transportés du bassin versant vers le fleuve Niger. De plus, la diminution du débit du fleuve Niger a contribué à ce qu'on appelle l'ensablement du bassin du Niger moyen.

2. Intérêt de l'étude

Les conséquences de la combinaison de l'augmentation du stock de sédiments disponibles et de la diminution des débits du fleuve Niger sont certainement nombreuses et variées, allant des étiages plus sévères, à des caractéristiques de crues variables et à un probable ensablement des projets d'aménagements hydrauliques le long du fleuve Niger. Les impacts négatifs potentiels de l'augmentation des apports de sédiments sur la vie aquatique, la navigabilité du fleuve et le traitement de l'eau ne sont pas négligeables et ont engendré débats et spéculations entre les scientifiques et les gestionnaires du bassin à propos des causes et de la sévérité des phénomènes observés, et générant les questions suivantes : cet « ensablement », s'il existe, est-il le fait d'un dépôt de sédiments ou seulement d'un lit mineur plus exposé?, en gros : y a-t-il moins d'eau ou plus de sédiments?

Les faits sont difficiles à séparer des perceptions du fait que les mesures directes des dynamiques sédimentaires dans la zone d'étude sont limitées ou inexistantes.

La présente étude est ainsi nécessaire en ce qu'elle contribue à comprendre l'évolution du bassin en termes de production et transfert de sédiments et leurs principaux facteurs de contrôle, sur une période ayant connu de rapides changements d'usage des sols. Elle peut aussi s'avérer utile aux gestionnaires de bassin dans la conception de mesures de contrôle des sédiments aussi bien que dans la programmation d'aménagements hydrauliques dans le bassin pouvant être affectés par la sédimentation.

3. Objectifs de l'étude

Le présent travail a pour but d'étudier le changement de couverture des sols et sa relation avec la production, le transport et le dépôt de sédiments dans le bassin du fleuve Niger moyen.

Plus spécifiquement, les objectifs seront de :

- Quantifier les changements de couverture des sols sur la période 1965 – 2000;
- Analyser le transport de sédiments dans le bassin du fleuve Niger moyen (afin de comprendre les principaux mécanismes, contraintes, ...);
- Evaluer l'influence du changement de couverture des sols sur:
    - Le transport de sédiment dans le fleuve Niger moyen,
    - La sédimentation croissante dans le fleuve;
- Determiner:
    - les modes de transport de sédiments prédominants,
    - les sources de sédiments,
    - les facteurs contrôlant le dépôt de sédiments,
    - les zones de sédimentation.

4. Approche de recherche

Le but de l'étude étant de comprendre la relation entre le changement de couverture des sols et la production de sédiments ainsi que d'étudier le transport de sédiments dans le bassin du fleuve Niger moyen, le travail de recherche a été menée de la façon suivante :

- Premièrement, des techniques de télédétection ont été utilisées pour obtenir une compréhension synoptique et une évaluation du changement de couverture des sols qui a eu lieu dans la zone d'étude au cours de ces dernières décennies.
- En second lieu, les facteurs climatiques, en particulier les précipitations et leurs impacts sur les débits, ont été étudiés dans la zone d'étude.
- Troisièmement, des campagnes de mesure des caractéristiques des sédiments et du lit des rivières (comme la concentration en sédiments et la granulométrie) ont été menées en différents sites le long du fleuve Niger moyen et de ses affluents. Une attention particulière a été portée au droit des confluences de trois affluents du fleuve Niger (deux rivières sahéliennes et une rivière soudanienne). Ceci avait pour but de quantifier la contribution des affluents à la charge sédimentaire du fleuve Niger. De plus, les mesures

ont été réalisées dans le but de comprendre et de quantifier les mouvements de sédiments le long du fleuve Niger moyen, en distinguant les zones d'érosion et de dépôt.

Les informations obtenues à partir de l'application des méthodes présentées ci-dessus ont été utilisées pour évaluer la relation entre la production de sédiments du fleuve Niger moyen et le changement de couverture des sols et ses effets associés, comme les ruissellements locaux croissants.

Les principaux résultats sont regroupés suivant les axes de recherche que sont les formes de la rivière et l'évolution du lit (partie II), l'analyse du changement de couverture des sols (partie III), l'hydrologie (partie IV) et l'analyse du transport sédimentaire (partie V).

5. Financements et collaborations

Dans le but d'améliorer la gestion des ressources du bassin du fleuve Niger, l'Autorité du Bassin du Niger (ABN) a exprimé le besoin d'obtenir une meilleure compréhension des dynamiques de transfert de sédiments notamment au regard des changements environnements continus.

L'étude a été financée à la fois par l'ambassade de France à Abuja au Nigeria par le biais de l'attribution d'une "Bourse du Gouvernement Français", par l'Autorité du Bassin du Niger (ABN), par l'Institut de Recherche pour le Développement (IRD) et par le Laboratoire de Transfert en Hydrologie et Environnement (LTHE) où la majorité du travail fut effectué.

L'étude a nécessité à la fois du travail sur le terrain, des analyses en laboratoire ainsi que des analyses de données, ce qui a été rendu possible par les collaborations de ces différentes institutions.

De plus, afin d'acquérir les données de débits utilisées dans cette étude, l'ABN a complété les moyens logistiques fournis par l'IRD pour le travail de terrain. Le centre régional Agrhymet a fourni un appui dans cette étude sous la forme de mise à disposition d'images satellite et de moyens informatiques. L'espace de travail nécessaire à l'analyse des échantillons d'eau et de sédiments a été fourni par les départements de Géographie et de Géologie de l'Université Abdou Moumouni à Niamey ainsi que par le laboratoire de génétique de l'IRD à Niamey.

Le Laboratoire de Géographie Physique (LGP) à Paris a fourni un appui sur les Systèmes d'Informations Géographiques. L'analyse granulométrique des matières en suspension, l'analyse des données et la bibliographie a été menée au LTHE à Grenoble, disposant d'un environnement de travail propice aux collaborations scientifiques.

Chapitre I – Zone d'étude et contexte environnemental

Introduction

Afin de pouvoir comprendre les résultats obtenus dans les chapitres suivants de cette étude, il est nécessaire de décrire les facteurs environnementaux qui influencent la zone d'étude. Le secteur d'étude est considéré dans le contexte plus large du bassin du fleuve Niger, un des principaux fleuves du monde. Le contexte environnemental de la zone d'étude est décrit par un examen des facteurs tels que la pluviométrie, l'hydrologie, la géologie, la podologie, la couverture végétale et la population.

Les modifications climatiques récentes et continues ainsi que la pression démographique rendent nécessaire l'étude de certains des facteurs directs et indirects qui influencent la production, le transport et le dépôt de sédiments dans la zone d'étude.

Le chapitre d'introduction a pour but de :

- Décrire la partie du fleuve Niger qui fait l'objet de cette étude;
- Décrire le contexte climatique général du secteur d'étude ainsi que son état actuel ;
- Faire une synthèse de la façon dont certains facteurs environnementaux tels que la géologie, les types de sol, la couverture végétale et la démographie peuvent influencer la production et le transport de sédiments ;
- Passer en revue les précédents programmes de suivi des sédiments réalisés sur le fleuve de Niger.

Conclusion

La zone d'étude et son contexte environnemental ont été décrits dans cette partie introductrice de l'étude.

- Les sols dans la zone d'étude sont essentiellement le produit de l'histoire géologique de la région. L'inventaire des sols de la zone montre que :
  - Les sols de la zone d'étude sont sensibles aux érosions éolienne et hydrique. De plus, des sols caractéristiques de dépôts géologiquement récents se trouvent le long du fleuve Niger.
  - Le type principal de sol dans les bassins du Gorouol et de la Sirba « les sols peu évolués régosoliques d'érosion » ou « sols minéraux bruts d'apport éolien ou volcanique », est typique des sols érodés et sur lequel les croûtes de surface se forment au début de la saison de pluies, freinant l'infiltration et augmentant potentiellement le ruissellement quand les sols sont nus. Les autres types de sols principaux ont une structure fragile et sensible aux érosions hydrique et éolienne.
  - Dans le bassin du Mékrou, le principal type de sol « sols lessivés » est un de ceux qui favorisent le transfert des particules d'argile de l'horizon de surface vers les cours d'eau.
- La zone d'étude connait une forte pression démographique avec une augmentation rapide de la population, qui a l'agriculture comme moyen de subsistance, et le bois de chauffe comme source d'énergie.
- Les programmes antérieurs de mesures de sédiments du fleuve Niger montrent qu'il y a une tendance a l'augmentation en matières en suspension le long du fleuve Niger, de sa source vers la zone d'étude.

Chapitre II – Forme et évolution du lit du fleuve Niger moyen

Introduction

La plupart des fleuves ont un comportement dynamique et s'ajustent en permanence aux changements climatiques naturels ou anthropiques. Ces procédés d'auto-ajustement sont tout d'abord verticaux et latéraux. Les changements de bandes actives des cours d'eau incluent le lessivage et le dépôt de sédiments, ainsi que la migration, l'élargissement ou la contraction de la bande active. Selon Montgomery et Buffington (1997), ils reflètent principalement les changements d'hydrologie et d'apport en sédiments des cours d'eau. Les changements géomorphologiques extrêmes des bandes actives de certains cours d'eau ont souvent des conséquences néfastes pour la navigation, les écosystèmes aquatiques et ils augmentent les risques d'inondation.

Les objectifs de cette partie sont de :

- Examiner la nature des changements à moyen terme (20 - 35 ans) de la forme en plan du lit de trois tronçons du fleuve Niger moyen, en utilisant une série multi temporelle d'images satellites ;
- Etudier le rapport entre les changements de géométrie des chenaux observée et l'hydrologie, les influences humaines et d'autres facteurs ;
- Déterminer les sources de sédiments potentielles et les formes d'érosion dans le bassin du fleuve Niger moyen ;
- Déterminer les changements à long terme des formes d'érosion et d'accrétion en comparant les données de niveau du lit de la rivière fournies par une campagne de mesures antérieure avec celles mesurées sur certains tronçons de la zone étudiée dans le cadre du présent travail.

Conclusion

- Suite aux analyses des changements de la forme du chenal du fleuve Niger moyen, les commentaires suivants peuvent être formulés :
    - On n'a pas observé de migration significative de chenal dans le fleuve de Niger moyen, qui est proche de ses conditions naturelles et normales en termes d'endiguement.
    - On démontre ici l'utilité des systèmes d'information géographique (SIG) pour l'évaluation précise du changement historique des formes en plan de fleuve utilisant des images de sources variées.
- Les changements les plus importants de forme du fleuve dans le secteur d'étude entre 1973 et 1999 sont récapitulés ci-dessous.
    - Les processus d'« anabranching » puis d'érosion des berges étaient les formes principales de réponse du chenal aux crues dans le fleuve de Niger moyen. Wende et Nanson (1998) ont postulé qu'en principe les reliefs peu prononcés, les chenaux végétalisés, et un environnement de type semi-aride à aride tel que les tronçons sahéliens 1 et 2, avec des écoulements en baisse et des concentrations de sédiments en augmentation, en aval rendent nécessaire des anabranches.
    - Pour chacun des trois tronçons étudié, la période autour de l'année 1984 correspondant aux débits les plus faibles a été la période au cours de laquelle le chenal du fleuve Niger moyen a subi les plus fortes perturbations.
    - La transformation du chenal se produit lentement dans le lit du Niger moyen; parfois avec un décalage entre l'occurrence des facteurs causant cette modification et la réponse de chenal.
- En plus des affluents du fleuve Niger moyen, les koris, nom donné aux oueds (cours d'eau éphémères qui sont caractéristiques du secteur autour de Niamey) ont été identifiés comme une source importante de fourniture de sédiment vers le Niger. •

Chapitre III – Changement de couverture des sols dans le bassin du fleuve Niger Moyen

Introduction

Les changements de couverture des sols peuvent être localisés ou plus étendus, et ils sont étudiés à partir d'observations au sol ou par télédétection. Les conséquences sur l'environnement des changements de couverture des sols sont variées, et elles peuvent avoir des effets rétroactifs sur le climat, comme le suggère Charney [1975].

Pour comprendre la dynamique de changement de couverture des sols dans la zone étudiée en relation avec la variabilité climatique et les impacts anthropiques, il a été nécessaire d'évaluer les changements de couverture des sols avec les données satellitaires disponibles.

Les images de télédétection permettent d'observer et de suivre des zones étendues, allant de l'échelle du tronçon de rivière à l'échelle du bassin versant, bien que cela nécessite un travail difficile et long et que cela soit coûteux. .

La télédétection est utilisée pour étudier le changement de couverture du sol en se basant sur le principe qu'un tel changement engendre une modification des valeurs de rayonnement [*J F Mas*, 1999]. La quantité et la qualité de rayonnement réfléchi reçu par une capteur de satellite dépend de la quantité, de la composition et des conditions à la surface du sol telles que la végétation, le sol ou la teneur en eau [*J Rogan et al.*, 2002].

Le but de ce chapitre est de caractériser l'évolution des occupations et couverts des sols (.végétation et sols dénudés) sur une période de 30 ans environ en utilisant des méthodes de télédétection afin d'évaluer leur propension à produire et transporter des sédiments dans la zone d'étude.

Les objectifs de ce chapitre sont les suivants :

- Quantifier les changements d'usage et de couvert des sols qui ont eu lieu dans la zone d'étude;
- Comparer les changements de couverture des sols de trois sous-bassins localisés dans l'aire étudiée ;
- Faire une étude bibliographique des effets des changements de couvertures des sols au Sahel.

CONCLUSION

Une des hypothèses de cette étude était que la forte diminution de la couverture végétale due aux facteurs climatiques et humains au Sahel causait une augmentation de la disponibilité en sédiments dans les cours d'eau sahéliens.

• L'étude a montré qu'il y avait un déclin intense de la couverture végétale dans les bassins du Gorouol et de la Sirba entre 1970 et 1999. La disponibilité en sédiments en particulier dans le bassin de Sirba pouvait être prévue à cause de l'augmentation considérable des sols nus arénacés entre 1975 et 1999.

• En revanche, le bassin soudanien de la Mékrou, qui a subi aussi le changement climatique,, a été affecté à un moindre degré par le recul de la végétation entre 1973 et 2000.

• En plus de l'utilisation des images Landsat à des résolutions spatiales et spectrales variables, l'étude a prouvé que lorsqu'elles sont disponibles, les images Corona peuvent être utilisées pour améliorer la quantité et qualité de l'information recueillie par la télédétection pour la couverture des sols dans le Sahel. Tandis que l'utilisation de ces images Corona exigent une capacité de traitement et de stockage informatique important, et sont chronophages pour la transformation et la classification, elles peuvent fournir des informations d'une grande valeur dans des zones sahéliennes où le relief est peu marqué et les déformations géométriques faibles en conséquence.

Chapitre IV- Eléments de l'hydrologie et mesures de débits

Introduction : Le fleuve Niger est-il en danger?

Les bassins versants constituent l'essentiel de l'espace des écosystèmes et fournissent de ce fait de nombreuses ressources aux riverains, en particulier dans les pays en voie de développement. La nécessité d'exploiter les ressources naturelles des bassins fluviaux pour les besoin des populations met parfois en danger ces mêmes populations riveraines ainsi que l'équilibre de la faune et de la flore.

Dans le bassin du fleuve Niger, du fait de la forte croissance démographique, les activités humaines telles que les prélèvements en eau, la navigation, les barrages, les rejets d'effluents industriels et domestiques et la surpêche pourraient constituer une menace pour le bon état du bassin si ces usages ne sont pas correctement gérés.

Le changement ou la variabilité climatique, avec ses impacts sur la pluviométrie, l'évaporation et les débits des cours d'eau du bassin du fleuve Niger et en particulier le bassin semi-aride du Niger moyen, rend encore plus complexe la gestion durable du bassin.

La conjugaison du changement climatique et de la pression anthropique croissante sur les ressources a quelques fois conduit à l'assèchement du fleuve Niger à Niamey au cours de ces dernières décennies. Cette pression risque de rendre encore plus difficile la tache routinière de régulation ou contrôle des sédiments, même pour un fleuve comme le Niger.

Cette partie de l'étude vise à étudier le bassin du fleuve Niger dans le contexte plus large des fleuves africains et à essayer de décrire les effets des changements environnementaux sur l'hydrologie du fleuve Niger moyen.

Pour atteindre ces objectifs, il sera nécessaire de :

- Caractériser le régime hydrologique du fleuve Niger moyen par rapport :
    - au régime hydrologique du Niger à l'amont de la zone d'étude;
    - à l'effet de la variabilité climatique et de la réduction des précipitations;
- Qualifier l'hydrologie du fleuve Niger à Niamey pendant la période étudiée au regard de l'hydrologie moyenne sur le long terme.

CONCLUSIONS

Les conclusions suivantes peuvent être tirées à la fin de la présente partie de l'étude : L'analyse hydrologique du cours moyen du fleuve Niger montre que :

• Les débits du fleuve dépendent en grande partie des précipitations et de l'influence de la diminution des précipitations sur le débit du fleuve Niger moyen. Le rôle de l'écoulement de base en soutenant les débits d'étiage du fleuve de Niger moyen a été démontré.

• L'hydrogramme moyen du cours moyen du fleuve Niger a deux maxima : un premier maximum caractérisé par une montée rapide qui se produit pendant la saison des pluies locale, et un deuxième maximum qui se produit en raison de la vidange du stockage de la delta intérieur (en amont de la zone d'étude). La première crue est plus prononcée dans le fleuve autour de Niamey et elle est moins prononcée à la fois vers l'amont vers l'aval de Niamey.

• Les affluents du Niger moyen n'ont pas répondu de la même manière que le fleuve lui-même aux changements climatiques et d'usages des sols. Le volume écoulé total à Niamey augmente par rapport à celui écoulé à Kandadji, une tendance qui ne peut pas être expliquée uniquement par l'augmentation des volumes écoulés des affluents mesurés. Le débit des cours d'eau éphémères pourrait également être en train d'augmenter. Une étude de ces ruisseaux pourrait fournir une meilleure compréhension de ce phénomène, en supposant que les pertes par évaporation, infiltration et prélèvements n'ont pas sensiblement évolué entre 1998 et 2008.

• La présente étude a été effectuée au cours d'une période relativement homogène d'augmentation de la contribution locale de l'écoulement aux débits de crue du fleuve Niger moyen.

La simulation du débit du fleuve réalisée en utilisant le modèle CARIMA du fleuve Niger (dans son état actuel) donne des résultats en bon accord avec des valeurs mesurées mais devrait être vérifiée sur une station hydrométrique contrôlée et jaugée pour qu'elles puissent être validées comme fiables.

Chapitre V-Transport de sédiments dans le bassin du fleuve Niger moyen

Introduction

La compréhension des dynamiques du transport des sédiments du fleuve Niger moyen est cruciale car en plus d'avoir un impact négatif sur la qualité de l'eau et sur les habitats aquatiques, les dépôts de sédiments risquent aussi de combler les ouvrages hydrauliques en rivière. Une meilleure connaissance du transport de sédiments dans le fleuve Niger est particulièrement importante pour la gestion du bassin notamment vis-à-vis de la diminution des débits.

Comparées aux études hydrauliques ou hydrologiques, les études de transport de sédiments nécessitent plus de données tout en fournissant en général des résultats moins précis. La principale information que cette partie de l'étude vise à apporter concerne les tendances à l'érosion et au dépôt le long du fleuve Niger.

Afin d'atteindre ce but, il a fallu :

- Mettre au point un programme de prélèvement de sédiments pour mesurer la concentration des sédiments en suspension le long du fleuve Niger et de certains de ses affluents, afin de quantifier les sédiments transportés dans la zone d'étude ;
- Analyser la granulométrie des matériaux du lit le long du fleuve Niger et de certains de ses affluents;
- Analyser la granulométrie des sédiments transportés en suspension par le fleuve Niger moyen et certains de ses affluents;
- Calculer la capacité de transport de sédiments en différents points le long du fleuve Niger à partir de données hydrodynamiques mesurées et modélisées.

CONCLUSION

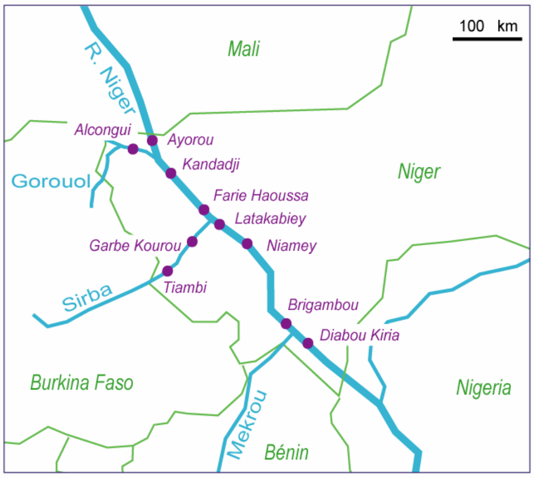
Cette recherche du transport des sédiments effectuée dans la présente partie de l'étude a pris en compte la composition des sédiments et la fréquence des prélèvements afin d'atteindre les objectifs de l'étude.

Une analyse granulométrique des particules des sédiments transportés en suspension par les cours d'eau dans le secteur d'étude au cours de la période d'étude a démontré :

- Les rapports complexes entre la taille des particules de sédiment, les débits des cours d'eau et les précipitations aussi bien que l'impact des effets saisonniers sur le transport des sédiments.

Les disponibilités de sédiment aux différentes stations le long le fleuve Niger moyen ont été déterminées en analysant l'évolution saisonnière des tailles de sédiment transporté en suspension au cours de la période d'étude.

- Le transport des sédiments à Ayorou a été noté comme ayant un approvisionnement limité, avec un pourcentage des particules très fines (0-40 µm) diminuant avec l'augmentation du débit du fleuve, même au début de la saison des pluies.



- Les sédiments très fins (0-40 µm) ont été transportés à Kandadji, Farié-Haoussa, Latakabiey et Diabou-Kiria, dans un rapport direct avec le débit du fleuve au début de la saison des pluies. Ceci indique que, du fait de l'impact des gouttes de pluie au début de la saison des pluies, les sédiments très fins sont disponibles pour être transportés.

- Le comportement des particules très fines (0-40 µm) et plus grosses (41-630 µm) à Niamey et Brigambou, indique qu'il y a deux sources distinctes de sédiments à ces stations pendant la phase de montée de l'hydrogramme au cours de la saison des pluies.

L'étude a identifié et a mesuré les sources de sédiment des affluents, les flux de sédiment sur ces affluents et tout au long du fleuve Niger moyen.

- Les apports de matières en suspension des affluents sahéliens principaux du fleuve Niger moyen (le Gorouol et la Sirba) ont été mesurés. Le flux calculé de sédiment du Gorouol était compris entre 480.000 et plus de 1 millions de tonnes par an pour la période d'étude. Le flux de sédiment mesuré pour la Sirba était entre 500.000 et 1.3 millions de tonnes par an pour la période d'étude. La variabilité du flux de sédiment était en grande partie due à la différence de volume total écoulé pendant une année de l'eau par les deux rivières. La différence des comportements d'offre et de transfert de sédiment des deux bassins sahéliens a été accentuée.

- Le bassin Soudanien de la Mékrou semble fournir moins de sédiment au fleuve Niger moyen au cours de la période d'étude, selon le bilan de sédiments entre les stations en amont et en aval de son confluent avec le fleuve Niger moyen.
- Le flux de matières en suspension le long du fleuve Niger moyen a été quantifié à partir des valeurs de concentration de MES et des débits mesurées ; il représente entre 11 et 16 millions de tonnes par an, avec un flux maximum se produisant autour de Niamey.
- L'étude a montré que d'autres sources significatives de sédiment existent entre Latakabiey et Niamey quoiqu'il n'y ait aucun affluent important entre ces deux stations. Les « koris » éphémères ont été avancés comme source probable pour ces sédiments en surplus, ce qui confirment les résultats obtenus dans la partie II de ce travail.

Les tendances au dépôt de sédiment le long du fleuve Niger moyen, le fonctionnement saisonnier ainsi que les facteurs de contrôle principal du dépôt de sédiment ont été mis en évidence dans cette étude.

- Une comparaison de concentration de MES et la capacité calculée de transport des sédiments du fleuve Niger moyen ont fourni une indication aux secteurs principaux de dépôt de sédiment et aux classes de taille de sédiment qui sont les plus exposés au dépôt. Le secteur autour de Niamey a été mis en évidence comme un domaine de dépôt de sédiment, en particulier du sédiment sableux entre le 126 et 630 μm.

Conclusions et Perspectives

1. Résumé Général

Le but de cette recherche à été de comprendre le fonctionnement sédimentaire du fleuve Niger moyen notamment pendant une période de dégradation des surfaces des bassins versants. L'étude a été menée en suivant trois axes principaux: l'analyse des couvertures végétales et des sols, l'analyses hydrologique, et les mesures et analyses sédimentaires.
Pour accomplir ce travail de recherche, cinq objectifs principaux ont été poursuivis.

- Le premier objectif était de décrire et quantifier les changements de couverture des sols qui ont eu lieu pendant les trois à quatre dernières décennies dans la partie sahélienne de la zone d'étude et de les mettre en comparaison avec la partie Soudanienne de la zone d'étude. L'hypothèse de fonctionnement était que dans la majeure partie de la zone d'étude, au cours de cette période, la végétation boisée a été remplacée par des surfaces de sol nues sous forme de terre cultivée, habitations humaines, et des bandes de végétation et de sol épuisés menant à une érosion plus élevée. L'analyse des changements d'usages des sols, bien que limitée par la disponibilité des images, en particulier pour les périodes anciennes, a montré que les surfaces de sol nues dans les bassins sahéliens ont augmenté entre les années 70 et 1999, de 60 % à 75 % pour le bassin du Gorouol et de 45 % à 71 % pour le bassin de la Sirba. Cependant, l'étude a montré qu'une légère réduction des surfaces de sol nues s'est produite entre 1992 et 1999, pour le Gorouol, et entre 1989 et 1999 pour la Sirba. Le bassin de la Mékrou a été peu affecté par la diminution de la couverture végétale entre 1973 et 2000, le pourcentage d'arbres a diminué seulement de 6 % entre 1973 et 2000. Cette tendance est comparable aux observations de la couverture des sols en particulier dans la région sahélienne. En résumé, l'analyse de la couverture des sols a montré que l'évolution des usages des sols est différente d'un bassin à l'autre, le changement le plus rapide se produisant dans les bassins sahéliens par opposition au bassin soudanien de la Mékrou. Cette étude a essayé d'incorporer les données des images Corona à l'étude du changement de couverture des sols du Sahel ; on a montré que tandis que l'utilisation de ce type de données est chronophage et demande beaucoup de ressources en stockage numérique, elles fournissent des informations utiles en particulier dans l'absence de données aéroportées ou de terrain fiables.
- Le deuxième objectif était de déterminer l'impact de la couverture des sols sur le transport des sédiments dans la zone d'étude. L'approche idéale à cette question aurait été d'effectuer une comparaison des caractéristiques de transport des sédiments pour deux voire plus des états distincts de couvertures des sols dans la zone d'étude. Bien que

l'évolution des couvertures des sols dans la zone d'étude ait été décrite dans la partie II de ce travail, et les données de MES (1976 à 1982) pour des parties de la zone d'étude étaient disponibles, la difficulté d'une comparaison directe des données de sédiment a été montrée dans la partie V de cette étude. Puisqu'il n'était pas approprié de faire une comparaison directe entre les données précédentes de sédiments et les données acquise pendant la présente étude afin de mesurer le changement de production de sédiment, des informations sur les conséquences du changement de couverture des sols ont dû être impliquées pour expliquer les phénomènes liées a ces changements. La tendance à l'augmentation des surfaces de sol nues démontrée dans la partie III de cette étude s'est produite en même temps que les apports croissants des affluents et les débits décroissants du fleuve à Niamey observés dans la partie IV de cette étude. Les phénomènes tels que la contribution croissante des affluents en combinaison avec les sols nus en extension, peuvent être prévus comme des causes potentielles de transfert de plus de sédiment du bassin vers le fleuve Niger moyen. En même temps, la diminution observée des débits du fleuve Niger moyen et la prédominance des débits de saison des pluies peuvent être vues comme des contraintes qui peuvent exercer un effet sur la capacité du fleuve Niger moyen de transporter efficacement les sédiments apportés

- Le troisième objectif de ce travail était d'étudier les changements de la forme du chenal du fleuve Niger moyen en réponse aux perturbations de débits du fleuve entre 1965 et 1999. On a observé que les changements de la largeur du chenal se produit avec un décalage d'environ 5 ans par rapport à l'occurrence des perturbations des débits sur le fleuve Niger moyen. On a observé que les changements importants de la forme du chenal du fleuve Niger moyen se sont produits dans la partie sahélienne de la zone d'étude. Le tronçon du fleuve Niger moyen près du Gorouol (tronçon 1), après une première augmentation de largeur du chenal du fleuve, s'est au contraire rétréci en raison du débit décroissant du fleuve. D'une part, le fleuve Niger moyen près de la Sirba (tronçon 2), en plus des fluctuations semblables à celles qui se sont produit dans le tronçon amont (tronçon 1) a montré une tendance à élargissement depuis 1989. Tandis que la légère augmentation des volumes écoulés annuels le long du fleuve Niger moyen n'a pas provoqué d'élargissement sur le tronçon 1, elle a causé un élargissement du chenal dans le tronçon 2. Ceci est dû à l'apport de la composante locale croissante de saison des pluies de l'hydrogramme pour le fleuve Niger moyen à Niamey (dans le tronçon 2) par rapport au tronçon amont (tronçon 1). Cette composante de l'hydrogramme, en plus d'assurer une augmentation des débits du fleuve, semble également fournir plus de sédiment, ce qui a pu être la cause de l'élargissement du tronçon 2 entre 1989 et 1999.

- Le quatrième objectif de cette étude était de quantifier le transport des sédiments du fleuve Niger moyen et de certains de ses affluents. Un protocole approprié de prélèvements de sédiments a été mis au point pour atteindre cet objectif. Des valeurs de concentrations de matières en suspension mesurées ont été transformées en valeurs instantanées de flux de sédiment. Des valeurs annuelles du flux de sédiment ont été calculées pour les stations le long du fleuve de Niger moyen et, enfin, l'entrée saisonnière des flux de sédiment par les deux affluents sahéliens a été calculée.
- Le cinquième objectif de cette étude était d'identifier des zones de source et de dépôts de sédiment et les facteurs principaux de ces phénomènes. Les effets de dénudation des sols et de l'érosion par écoulement de surface ont été démontrés par la croissance des dépôts alluviaux. A titre d'exemple, la superficie de l'une de ces zones de dépôt alluvial près de Niamey est passée d'environ 0.16 km ² en 1975 à environ 1.24 km² en 1999. Les dépôts de sédiments de cette nature sont une source de sédiment pour le fleuve Niger pendant la saison des pluies. En ce qui concerne la dynamique de dépôt de sédiment dans la zone d'étude, l'hypothèse de travail était que les taux de dépôt le long du fleuve Niger moyen sont contrôlés par les forces liquides et des forces de résistance dues aux caractéristiques des particules de sédiment. Les analyses de transfert de sédiment effectuées dans la partie V ont indiqué que pour toutes les classes de taille et pendant toutes les phases de débits du fleuve, le tronçon entre Latakabiey et après Niamey est le domaine principal du dépôt de sédiment.

L'évaluation de la méthodologie appliquée à l'étude

Cette étude a appliqué une série de méthodes et approches afin d'atteindre les objectifs d'ensemble.

L'utilisation des images satellitaires quand elles étaient disponibles, pour le suivi de la forme du chenal du fleuve et du dépôt de sédiment, en utilisant une plate forme de SIG, a fourni un outil important dans la quantification des changements historiques dans la grande zone d'étude. Bien que les données satellites puissent fournir des informations sur les états passé et présent de la couverture des sols, l'utilisation la plus précise de cette méthode est possible quand des données de vérité terrain au sol sont obtenues en même temps que les images. L'étude a montré que des données de CORONA pourraient fournir des informations qualitatives aussi bien que quantitative pour les études semblables. Le prélèvement de MES simple mais fréquent combiné avec le prélèvement en travers (plusieurs prélèvements dans la section) occasionnel semble être une méthode rentable et raisonnablement précise pour la surveillance d'un grand fleuve comme le Niger.

2. Perspectives de travail

L'établissement d'un programme de mesure de sédiments qui prend en compte la composition en taille de sédiment comme mis en évidence dans cette étude fournirait à des directeurs d'agence de bassin plus d'information sur la dynamique de sédiment de la zone d'étude qu'il n'a été possible de le faire au cours de la période d'étude.

L'importance des mesures de débit du fleuve dans le bassin moyen du fleuve Niger n'est pas surestimée ici, parce que ces débits sont importants pour des études et pour la compréhension de changements de l'hydrologie et du transport des sédiments. L'utilité des outils pour simuler la propagation des crues du fleuve a été mise en évidence, sous condition que les résultats qu'ils produisent soient correctement vérifiés. De tels outils doivent être mis à jour régulièrement afin de maintenir l'exactitude des résultats disponibles.

Les résultats de cette recherche ont montré l'existence de sources significatives de sédiment autres que les affluents jaugés du fleuve Niger moyen. C'est particulièrement vrai autour de Niamey. Afin d'améliorer la connaissance de la dynamique de sédiment dans la zone d'étude, il semble nécessaire d'étudier l'écoulement et les caractéristiques de sédiment de ces cours d'eau éphémères connus sous le nom de « koris » qui existent dans ce secteur.

Cette recherche a montré que les ressources en eau dans la zone d'étude sont fortement influencées par la variabilité climatique, et que les régimes et quantités des écoulements sont des facteurs importants qui contrôlent le transport et dépôt de sédiments. Une collaboration avec des programmes de recherche, tel que AMMA (Analyses Multidisciplinaires de la Mousson Africaine) qui vise à améliorer la compréhension de la mousson de l'Afrique de l'ouest et ses influences sur l'environnement et les ressources en eau, pourrait aider à prévoir les effets possibles des futures variabilités climatiques sur le transport sédimentaire dans la région. De plus, les impacts des projets de futurs ouvrages hydrauliques peuvent être étudiés dans le cadre d'une telle collaboration.

3. Conclusions

La recherche présentée dans ce document représente une tentative d'améliorer la compréhension des impacts d'un environnement en plein changement dû aux facteurs climatiques et anthropogènes sur le transport des sédiments dans le fleuve Niger moyen. Les effets de l'accroissement des surfaces de sol nues sur le transfert de sédiment vers le fleuve Niger moyen sont démontrés en termes de contribution croissante des affluents, augmentant les débits de saison des pluies du fleuve Niger moyen et augmentant la taille des secteurs de dépôts alluviaux. La discontinuité spatiale et temporelle dans le flux de sédiment observé le long du fleuve de Niger moyen entre Latakabiey, Niamey et Brigambou, est expliquée par les résultats obtenus grâce aux analyses de dépôt de sédiment du fleuve Niger moyen. Ce travail de recherches, en plus de fournir les clés des connaissances de base sur le fonctionnement du transfert de sédiment du fleuve Niger moyen, peut être utile aux directeurs de bassin et les ingénieurs dans la planification pour les travaux hydrauliques le long du fleuve et comme base pour la comparaison pour le futurs études sédimentaires dans le secteur.